ALTERNATING-CURRENT RAILWAYS

(PART 2)

SINGLE-PHASE RAILWAYS

SERIES ALTERNATING-CURRENT MOTOR

INTRODUCTION

1. Types of Motors.—The advantages obtained by the use of alternating current for long-distance railway lines with heavy trains are possessed by the single-phase system as well as by the three-phase system. The development of the single-phase system was, however, long delayed by the lack of a suitable single-phase alternating-current motor, and at present only two types are in use; these are the *alternating-current series motor* and the *compensated repulsion motor*. The alternating-current series motor was first developed, in 1902, by the Westinghouse Electric and Manufacturing Company of America, but is now made by many other firms. It will work satisfactorily with either alternating or direct current. The compensated repulsion motor, or *Winter-Eichberg motor*, as it is sometimes called after its inventors, is manufactured by the Allgemeine Elektricitats Gesellschaft, in Germany.

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OPERATION OF SERIES MOTOR ON ALTERNATING CURRENT

2. General Construction of Motor. — The **alternating-current series motor** is similar in construction to a direct-current series motor, but is fitted with laminated field cores and yoke as well as laminated armature core, in order to prevent excessive loss due to eddy currents which would be set up in a solid mass of iron by the reversals of magnetic flux. In order to improve commutation by reducing the current in the armature coils which are short-circuited by the brushes, the leads from the coils to the commutator segments are made of high-resistance material, and are much longer than they would be for a motor designed to operate on direct-current circuits. The inductive effects of the armature are more or less completely neutralized by a *compensating* or *neutralizing winding*, which is distributed in slots in the pole faces. The current circulates in the compensating winding in a direction opposite to that in the adjacent armature conductors.

3. Direction of Rotation.—When an alternating current flows through the field and armature windings of a series motor, the polarity of the field pole pieces and the direction of the current

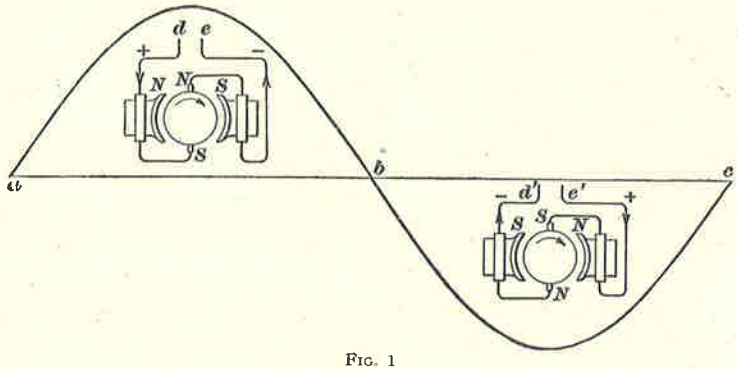

FIG. 1

in the armature conductors change at practically the same instant, so that the relation between them is unchanged and continuous rotation in a given direction is therefore maintained. In Fig. 1, curve $a\,b\,c$ represents one cycle of an alternating current. In the portion of the cycle $a\,b$, the current is assumed to flow from motor lead d to lead e, resulting in the north N and south S polarity of fields and armature cores and the direction of rotation shown by the arrow. At b, the direction of flow of current is reversed; it now flows from lead e' to lead d', thus reversing the polarity S and N of field poles and armature poles, but not the direction of rotation, which remains unchanged, as indicated. In the case of an alternating-current motor, as well as of a direct-current series motor, the direction of rotation is not reversed where both the field terminals and the armature terminals are reversed, but the rotation is reversed when either the field terminals or the armature terminals are reversed.

COMPENSATION FOR INDUCTANCE AND ARMATURE REACTION

4. Effects of Inductance.—When a current flowing through a coil changes in value, the number of lines of force embraced by the coil also changes, and this change in the number of lines sets up an E.M.F. in the coil. The induced virtual E.M.F. is proportional to the inductance of the coil and to the frequency of the change in current. In a motor used on an alternating-current circuit, the induced E.M.F. tends to make the current supplied to the motor lag behind the voltage impressed on the motor terminals, thus giving a low power factor. As it is desirable to have as high a power factor as possible, the inductance of the motor windings is made as small as possible.

In the case of the main field windings of a series motor, the induced E.M.F. is reduced to its lowest value by reducing the number of turns of the field coils to the minimum which will give the necessary magnetic flux with the current flowing.

5. Action of Compensating Winding.—An extra field winding is provided on alternating-current series motors, the effect of which is to neutralize or compensate for the inductive effect of the armature coils, and the winding is therefore called a **compensating winding.** The compensating winding, main field winding, and the armature are all connected in series. The compensating action depends on the fact that, if means are

provided for subjecting the coil, the inductance of which is to be neutralized, to the effects of induction from a second coil having an opposing magnetic flux, both coils will be practically free from inductance, and the same value of either direct or alternating E.M.F. will send the same current through the coils. This is the effect of the action of the compensating coils on the armature coils, and the armature coils on the compensating coils. In addition to reducing the inductive effect of the armature coils and compensating coils, and thereby improving the power factor of the motor, the current in the compensating winding so neutralizes the armature reaction that proper commutating conditions may be secured with fewer turns on the field winding, and thus with a weaker field, than would otherwise be possible.

6. The action of the compensating winding is shown in Fig. 2, which is the development of a portion of the windings

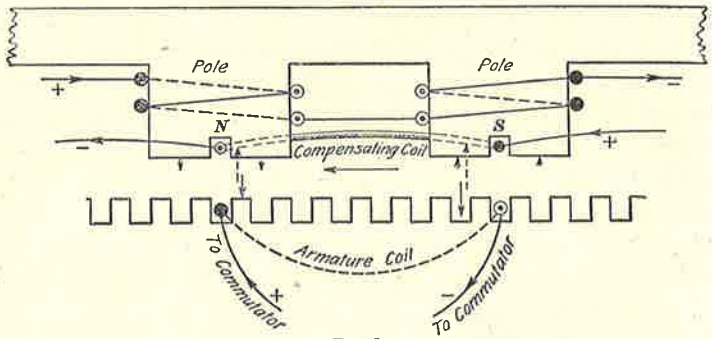

FIG. 2

of a compensated single-phase alternating-current series motor The direction of motion of the armature core is indicated by the large horizontal arrow. Only one armature coil and its corresponding compensating coil are shown. In the actual motor there are numerous armature coils and compensating coils, the armature coils being placed in slots in the armature core and the compensating coils, having much the same distribution, in slots in the pole faces. Two pole pieces and two main field coils are shown, as well as the resulting polarity,

north N and south S, of the poles when the current is flowing through the field coils in the direction indicated by the arrowheads.

7. In order to obtain rotation in a given direction, there must be a certain relation between the polarity of the pole pieces and the direction of current flow in the armature conductors under the poles. With the polarity as shown in Fig. 2, and the indicated direction of rotation, the current in the armature coil flows in a counter-clockwise direction when viewed from the lower portion of the illustration. The current is an alternating one, so that, while the coil is passing from contact with one brush to contact with the next, the current through the motor windings may reverse several times. At the instant under consideration, the current in the armature coil tends to set up a magnetic flux in the direction indicated by the full-line vertical arrows.

8. The compensating coil is so connected that the current flowing through it has a tendency to set up a magnetic flux in the direction indicated by the vertical dotted arrows, Fig. 2. These two magnetic fluxes oppose each other. If the current reverses, both magnetic fluxes are reversed in direction, and therefore still oppose each other. These fluxes practically neutralize each other in their action on the sets of coils. The compensating coil is not always connected in series with the main motor windings. In some types of motor it has no external connections at all, and is merely short-circuited on itself. In this case it acts as the short-circuited secondary of a transformer, and is quite effective in neutralizing the effect of inductance of the armature.

9. **Relative Arrangement of Coils.**—The relative arrangement of armature, pole pieces, main field coils a, and compensating coils b, c, d, e for a four-pole motor is shown in Fig. 3. The armature, if of large size, is usually parallel-wound and arranged for more than a four-pole field. It is assumed that at a given instant the alternating current is flowing in such a direction through the main exciting field coils, the armature, and the

compensating coils as to tend to make the top and bottom pole pieces north poles N and the side pole pieces south poles S; to make two north poles N_a and two south poles S_a at the points indicated on the armature core; and to make the inner sides of compensating coils e and c north poles N_c, and the inner sides of compensating coils b and d south poles S_c. The directions of these various sets of lines of force are indicated by short arrows and arrowheads.

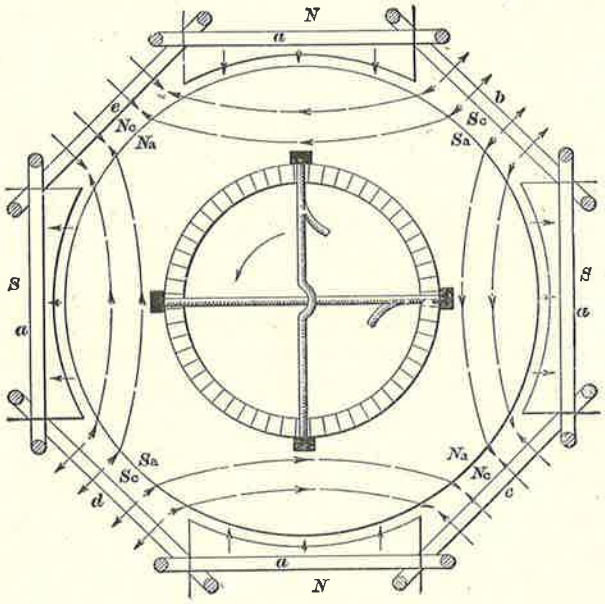

FIG. 3

10. When the current reverses, the polarities at all of the poles shown in Fig. 3 are also reversed. As, in practice, the compensating winding is distributed over the pole faces, and is so connected that the current in the turns of the coils tends to set up in the pole faces and between the pole tips lines of force that directly oppose the lines of force caused by the current in the adjacent armature coils, the inductance of the compensating winding and the armature winding is nearly, but not entirely, neutralized, as is also the distorting effect of the armature current on the field strength.

E.M.F.'s DEVELOPED IN ARMATURE

11. Speed and Transformer E.M.F.'s.—When the armature of an alternating-current series motor is rotating in the magnetic field set up by the main exciting coils, a counter E.M.F. is generated in the armature coils in the same manner as in the armature of a direct-current motor. This E.M.F. will be referred to as the **speed E.M.F.**, because it is due to the rotation of the armature. In an alternating-current motor there is also set up in the armature coils an E.M.F. due to the alternating magnetic flux passing through the pole pieces and armature. This E.M.F. is due to transformer action, and will be referred to as the **transformer E.M.F.** The speed E.M.F. is proportional to the speed; the transformer E.M.F. is proportional to the frequency of the alternating current. The speed E.M.F. is the useful one, as it is the counter E.M.F. of the motor. The effect of the transformer E.M.F. in part of the coils is neutralized by the effect of the same E.M.F. in the remaining coils.

12. Direction of Speed E.M.F.—The relative directions in which the speed E.M.F.'s developed in an armature act are indicated in Fig. 4 by the full-line arrows. A ring-wound armature is shown, as the diagram is thus made more easy to follow than if a regular drum winding were illustrated. Assuming that the polarities of the pole pieces at a given instant are north N and south S as marked, and the direction of rotation as indicated by the long curved arrow, the directions of the counter E.M.F.'s are away from brushes b and d and toward brushes a and c.

13. Direction of Transformer E.M.F.—The direction in which an induced E.M.F. acts round a coil depends on the direction of the lines of force in the coil and whether their number is increasing or diminishing. It may be determined by the following rule:

Rule.—*If the effect of the magnetic action is to diminish the number of lines of force that pass through the coil, the E.M.F. will act round the coil in a clockwise direction, as viewed by a*

person looking along the magnetic field in the direction of the lines of force. If the effect is to increase the number of lines of force that pass through the coil, the E.M.F. will act round the coil in a counter-clockwise direction, as viewed by a person looking along the magnetic field in the direction of the lines of force.

14. In Fig. 4, the alternating magnetic flux at a given instant is supposed to be increasing in value, and is of the polarity indicated by the letters on the pole pieces. Standing at point *e*,

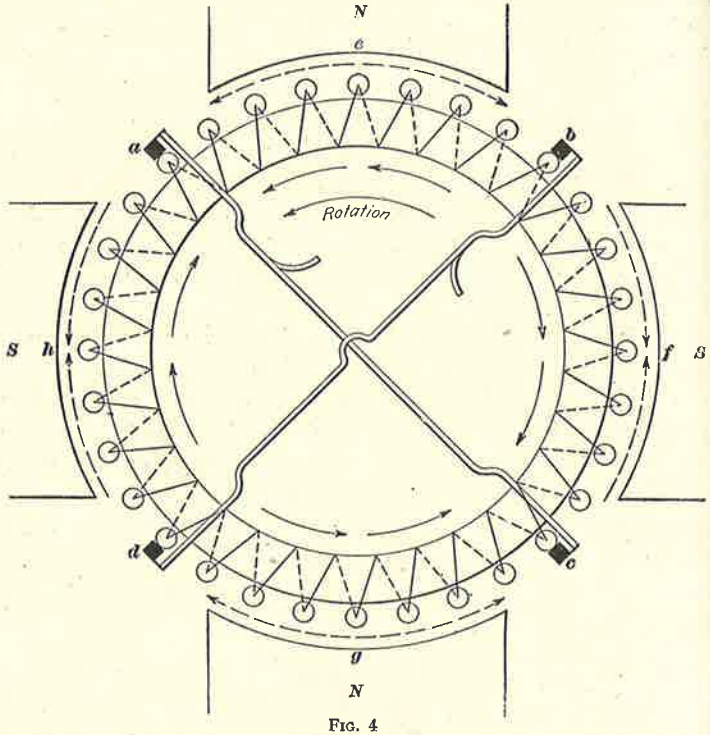

FIG. 4

and looking along the lines of force toward *h*, the increasing magnetic flux will set up an E.M.F. that will tend to send a current round the turns of wire in a counter-clockwise direction; that is, the transformer E.M.F. is from *e* to *h*. By similar reasoning, the other transformer E.M.F.'s are found to be from *e* to *f*, from *g* to *h*, and from *g* to *f*, as indicated by the long

dotted arrows. In the set of coils between any two brushes, it should be noted that the transformer E.M.F. in one half of the coils is directly opposed by the transformer E.M.F. in the other half of the same set of coils. These E.M.F.'s therefore neutralize each other, and the speed E.M.F. is affected but little, provided the brushes are on the neutral points.

15. E.M.F.'s in Drum Winding.—A developed winding of a parallel-wound four-pole drum armature is shown in Fig. 5. The field magnetic flux is assumed to be increasing in value and of the polarity indicated by the letters *N* and *S*. The directions

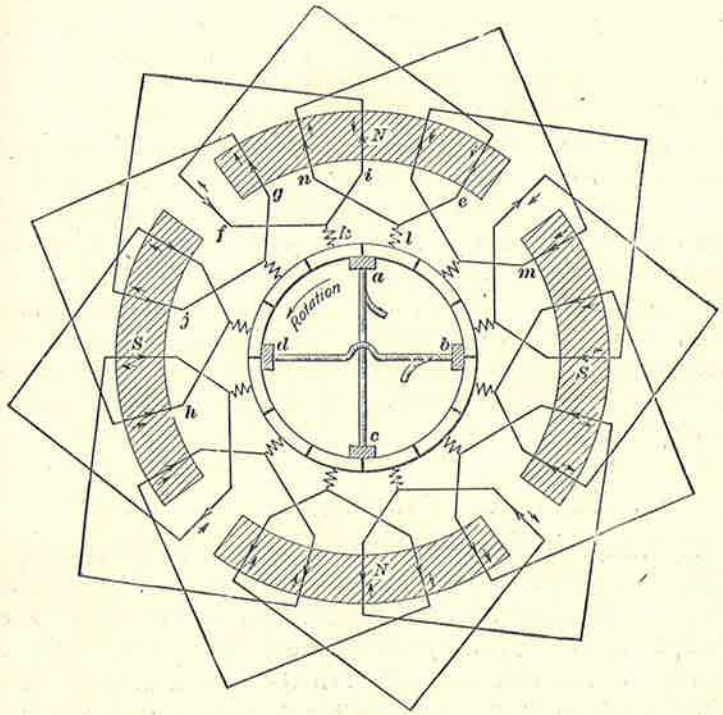

FIG. 5

of the speed or counter E.M.F.'s are indicated by the arrowheads on the conductors. Lines of force are assumed to be coming up through coil *e f* from the north pole below it. The transformer E.M.F. tends to send a current round the coil of such

direction that, if it actually flowed, it would set up lines of force opposite in direction to those emanating from the pole piece. The flow of current in coil *e f* would thus be clockwise, as indicated by the short arrows near the conductors, and the direction of the lines of force would be downwards through the coil.

16. Where an armature coil is opposite parts of both a north pole and a south pole, the pole having the larger portion of the magnetic flux passing through the coil is assumed to exert the greater influence. For instance, in Fig. 5, coil *g h* lies partly over a north pole, but mostly over a south pole, and as the lines of force are increasing in value and are passing down through the coil into the south pole, the transformer E.M.F. is in a counter-clockwise direction. This E.M.F. tends to set up a current that will in turn set up lines of force passing up through the coil, these lines being opposite in direction to the main field lines passing into the south pole. It should be noted that in coils *i j* and *g h*, which are connected between brush *a* and brush *d*, the speed E.M.F. is in a counter-clockwise direction in both coils, but that in coil *i j* the transformer E M.F. is clockwise, while in coil *g h* it is counter-clockwise. The transformer E.M.F.'s thus neutralize each other so far as their effect on the speed E.M.F. is concerned. The same conditions hold true for the other quarters of the winding between brushes *a* and *b*, *b* and *c*, *c* and *d*.

COMMUTATION AND COMMUTATING POLES

17. Voltages in Short-Circuited Coils.—When two commutator segments are under a brush at the same time, the coil which is connected between them is short-circuited by the brush. For example, in Fig. 5, coil *e f* has its ends connected by brush *a*. During the time that each coil is short-circuited there are two E.M.F.'s set up in it, known as the *reactance voltage* and the *transformer voltage*.

18. Reactance Voltage.—At the instant that each coil comes under the brush and is short-circuited, it is carrying the full current which is circulating in the armature winding. As soon

as the coil is short-circuited this current commences to die away, and must pass through zero value and rise to full value in the opposite direction before the coil is disconnected from the brush. Every current-carrying conductor is surrounded by a magnetic field of its own, and as the current changes in value, this magnetic field changes also and cuts the turns of the short-circuited coil, thus setting up an E.M.F. of such a direction as to tend to oppose the change in the current. This E.M.F. is known as the **reactance voltage.**

19. Transformer Voltage.—The short-circuited coil *e f*, Fig. 5, at the instant shown, is opposite the pole piece *N*, and as the polarity of the pole piece is periodically changing, an alternating magnetic flux is set up through the coil as it moves past the pole. The coil acts as the secondary of a transformer, of which the field winding on the pole piece *N* is the primary, and the E.M.F. developed is therefore called the **transformer voltage.** The resultant voltage acting in each coil as it is short-circuited is composed of the reactance and transformer voltages. As the ohmic resistance of the closed circuit is low, a very large current will flow through the coil and cause violent sparking at the brushes when the local circuit is broken if precautions are not taken to prevent it. In order to reduce the short-circuit current, usually only one turn per coil is used, a low frequency of the alternating current is employed, a low value of E.M.F. is applied to the motor terminals, and the magnetic circuits are carefully designed.

20. Resistance Leads.—A method used by some manufacturers to reduce the short-circuit current is to connect the junctions of the coils to the commutator segments with leads of resistance metal, as shown at *k, l*, Fig. 5. The resistance of these leads *k, l* prevents an excessive current from flowing through the local circuit composed of the coil *e f*, the leads *k, l*, the two commutator bars, and the brush *a*. The leads carry current only when the commutator bars to which they are connected are in contact with the brushes, as the armature windings form a closed circuit independent of the leads. The loss occasioned by the resistance of the few leads in circuit at the brushes at any time

is slight. In small alternating-current armatures, such as are used in motors for driving air compressors, no resistance leads need be used, as the brushes usually have sufficient resistance to limit the short-circuit current.

21. In railway motors of ordinary size, the resistance leads are usually tapped to the armature winding at the rear end of the core and brought to the commutator segments through the same slots as the main winding. In some of the large locomotive motor armatures, in order to secure a greater length, the leads are tapped to the armature winding at the front end of the core, carried to the rear end, doubled back to the front end, and then connected to the commutator. In case a short circuit should occur in the field windings or in the armature, the transformer voltage set up by the alternating magnetic flux will cause an excessive current to flow through the short-circuited section and perhaps result in a burnout.

22. Use of Commutating Poles.—A method of reducing sparking at the brushes of a railway motor, which is very successful in practice, is to induce in the short-circuited coil a voltage which is equal and opposite to the resultant E.M.F. due to the reactance and transformer actions. This is effected by providing the motor with small **commutating poles** situated between the main poles. The windings of these commutating poles are supplied with current of such strength and phase that, when the short-circuited coil revolves in the field set up by the commutating-pole windings, the voltage generated in it neutralizes the reactance and transformer voltages almost completely. In order that the current in the windings of the commutating poles shall be of the correct strength and phase, these windings are connected in many ways. They are in some cases connected in shunt with the motor, either by themselves or in combination with resistances or choking coils; in other cases they are fed by a special transformer or autotransformer connected in parallel with the armature. In some types of motors, both resistance leads in the armature and commutating poles have been used to reduce sparking.

23. Connections of Commutating-Pole Windings.—Some of the methods of connecting the windings of the commutating

poles of alternating-current series motors are shown in Fig. 6. In each case the main field winding *a* is connected in series with the armature *c*, but the compensating winding *b* and the commutating-pole winding *d* have various connections. In the arrangement shown at (*a*) the commutating-pole winding *d* is connected in parallel with a non-inductive resistance *e*. The field set up by the current flowing through winding *d* will be

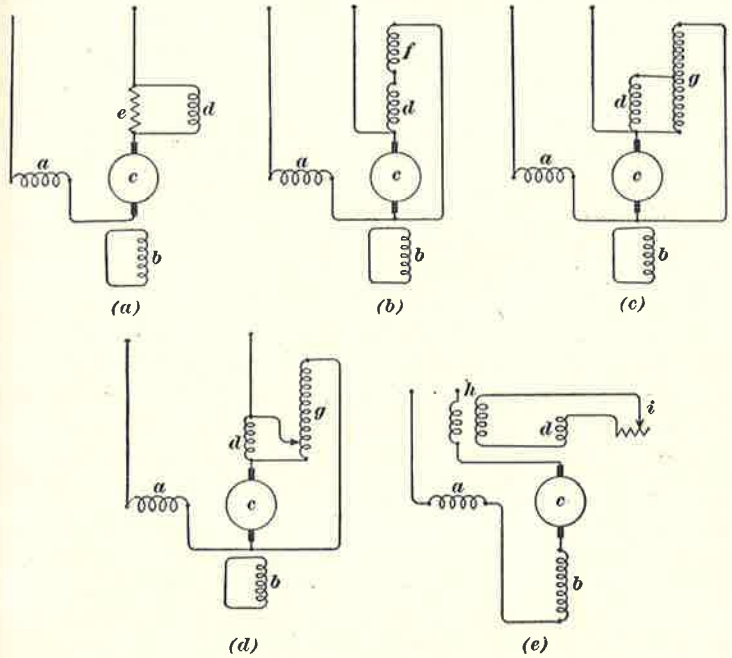

FIG. 6

nearly 90° out of phase with the current in the main circuit of the motor, and will therefore have the proper phase relation to neutralize the transformer voltage in the armature coils short-circuited by the brushes.

24. The arrangement ot the various windings of an alternating-current series motor shown in Fig. 6 (*b*) has the advantage of avoiding a resistance in series with the motor. The commutating winding *d* is connected in series with a choking

coil *f*, and the two are connected across the terminals of the armature *c*. Owing to the inductive effect of both windings *d* and *f* the current through them, and consequently the flux set up by winding *d*, will have such a phase relation with the main current as to give a good commutating field.

In Fig. 6 (*c*) the commutating-pole winding *d* is connected across half the winding of an autotransformer *g*, which is joined in parallel with the armature *c*. This arrangement gives practically the same effect as that shown at (*b*). In the arrangement shown in view (*d*) the commutating-pole winding *d* is joined in series with the motor, and in addition is connected to an autotransformer *g* which is in parallel with the armature. The phase relation of the current in winding *d* to the main current may be varied by changing the connection to the autotransformer, so that it is fairly easy to adjust the commutating field for any given conditions.

25. A method of exciting the commutating-pole winding *d* from a series or current transformer *h* is shown in Fig. 6 (*e*). Regulation of the strength of the commutating field is made by means of an adjustable non-inductive resistance *i*. The compensating winding *b* is connected in series with the motor instead of being short-circuited, as shown in the arrangements previously described. The effect obtained is essentially the same with either method of connection of the compensation winding.

PHASE RELATIONS OF VOLTAGES AND CURRENT

26. Voltage in Main Field Coil.—When an alternating-current motor is connected to the mains, the main field winding acts as a choking coil, and has generated in it a counter E.M.F. due to the inductance, which introduces into the alternating-current motor a voltage that is not present in the direct-current motor, and increases the total voltage required for the operation of the motor. As the field coil, armature, and compensating coil are in series, the voltages across the several sections of the winding may be considered as making different phase angles with the current flowing in series through the whole winding.

In such a case, the total voltage will not be the numerical sum of the several voltages, as the difference in phase relation must be considered.

27. Vector Diagram.—The total voltage across the terminals of the motor may be determined by the aid of a vector diagram similar to Fig. 7. When two forces acting in different directions

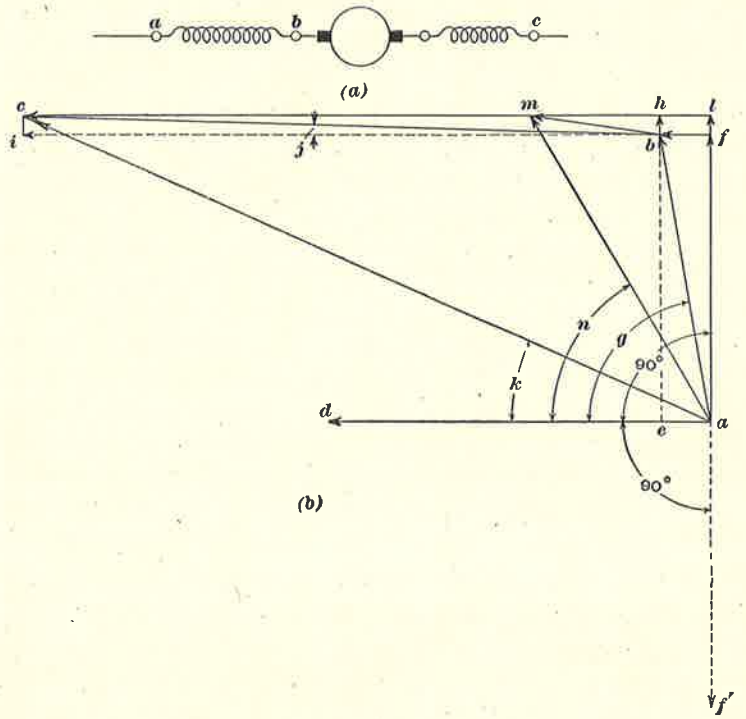

FIG. 7

are represented by the lengths and directions of two joined lines, the force in one line acting from its free end toward the junction of the two lines, and the force in the other line acting from the junction toward its free end, the value and direction of the force necessary to balance the combined effects of the two forces are indicated by the length and the direction of the line connecting the free ends of the two lines. The direction

of this force is taken as opposing the general direction of the forces in the two original lines, which constitute two sides of the triangle of forces thus formed. In Fig. 7 (*a*) is shown the motor circuit, and in (*b*) the corresponding voltage diagram. The sketches are so lettered that line *a b* in view (*b*) represents the voltage across the field coil *a b* in view (*a*); line *b c* in (*b*), the voltage, under running conditions, across the armature and compensating coil *b c* in (*a*); and the resultant line *a c*, in view (*b*), represents the total voltage across the motor terminals *a c* in view (*a*).

28. The directions of the current and voltages are indicated by arrowheads. The value of the current *a d*, Fig. 7 (*b*), is laid off on the horizontal line through *a*. As the field coil has inductance, the voltage *a b* required to drive the current through the field coils is the resultant of two components, one component *a f* necessary to overcome the counter E.M.F. due to inductance of the coil, and the other *f b*, or *a e*, necessary to force the current against the ohmic resistance of the coil. The E.M.F. due to inductance lags 90° behind the current, as shown at *a f'*, so that the voltage *a f* to overcome it is 90° in advance of the current. The voltage *a e* to overcome the ohmic resistance and supply the losses is in phase with the current. It should be noted that *f b* is short in comparison with *a f*; therefore the angle of lag *g* of the current *a d* behind the E.M.F. *a b*, applied to the field coil, is nearly 90°.

29. Voltage Across Armature and Compensating Coil.—There is little inductance in the combined armature and compensating coil of a series alternating-current motor, as is shown by the line *b h*, Fig. 7, which represents the reactance drop. Under running conditions the energy component *h c* of the applied voltage is large, since it represents the pressure *h m* necessary to overcome the drops in the armature and compensating coils due to their ohmic resistances and the voltage *m c* required to balance the speed E.M.F. The speed E.M.F., which is in phase with the current, multiplied by the current gives the electrical power transformed into mechanical power. The resultant of *b h* and *h c* represents the voltage applied to the combined armature

and compensating coil, and is the diagonal *b c* of the parallelogram *b h c i*. The applied voltage will be nearly in phase with the current, as shown by the small angle of lag *j*. The direction of the current is indicated by the line *b i* parallel to *a d*.

30. Running Voltage.—The resultant *a c*, Fig. 7, of the voltage *a b* across the field windings and the voltage *b c* across the armature and compensating coil is the voltage applied to the motor when running, and is found by drawing a line joining the points *a* and *c*. The direction of this voltage is from *a* to *c*, as indicated by the arrowhead, and the current *a d* lags behind pressure *a c* by the angle *k*. In the triangle of forces *a b c*, the general direction of the arrowheads on sides *a b* and *b c* is counter-clockwise, while the arrowhead on *a c* indicates a clockwise direction round the triangle. The running voltage *a c* may also be considered as the resultant of the total inductive component of the voltage $a\,l = a\,f + b\,h$ combined with the total energy component $l\,c = f\,b + h\,c$.

31. Starting Voltage.—If the motor is starting and the terminal E.M.F. is reduced so that the current through the motor windings is the same as the running current, the lines *f b*, *a f*, *b h*, and *h m*, Fig. 7, representing, respectively, the E.M.F.'s necessary to overcome the resistance and reactance drops of the field coils and the combined armature and compensating coils, may remain practically unchanged. The energy component *h m* of the combined armature and compensating coil is now small. Since the developed power at starting is inconsiderable, this component represents the voltage necessary to force the current through the ohmic resistance of the armature and compensating coil. The resultant pressure *b m* represents the voltage across the armature and compensating winding *b c*, Fig. 7 (*a*), under starting conditions. The line *a b*, Fig. 7 (*b*), representing the voltage drop across the field winding remains unchanged, as the current value is assumed to be the same as under running conditions. The starting voltage *a m* is the resultant of *a b* and *b m*, and represents approximately the E.M.F. which should be applied to the motor terminals when starting in order to keep the current down to the value represented by *a d*.

32. Power Factor.—The angle of lag k, Fig. 7, between the running voltage and the current is much less than the angle of lag n between the starting voltage and the current. Therefore, the current in the first case is more nearly in phase with the E.M.F., and the power factor under running conditions is much higher than under starting conditions. If the inductance of the armature had not been neutralized by the action of the compensating coil, the power factor would have been lower under both starting and running conditions. At starting, the counter E.M.F. due to the field-coil inductance has a much greater effect on the total motor voltage than under running conditions, due to the inductive component not changing greatly, while a great change takes place in the energy component. With alternating current, the starting voltage is a larger proportion of the final running voltage than when direct current is used on the same motor and under similar conditions.

CHARACTERISTICS OF SERIES ALTERNATING-CURRENT MOTOR

33. Speed.—The speed at which the armature of an alternating-current series motor rotates depends on the voltage applied to the motor terminals and on the load. In this respect the motor resembles its direct-current counterpart, and the speed of the motor is readily regulated by varying the applied voltage. The alternating-current motor possesses the advantage, however, that the voltage applied to the motor terminals can be varied by means of a transformer, without waste of energy in resistances. The maximum pressure applied to a single motor seldom exceeds 350 volts, as it is difficult to design satisfactory motors for a higher voltage.

34. Characteristic Curves. — The characteristic curves of a 210-horsepower railway motor for various terminal voltages are given in Fig. 8. The curves a to g, view (a), show the speed, in miles per hour, of the locomotive carrying the motor, at voltages ranging from 150 to 320. They are plotted with the current taken by the motor as abscissæ. The efficiency of the

motor and its gearing at various voltages and currents is shown by curves h to n. The tractive effort exerted by the motor at

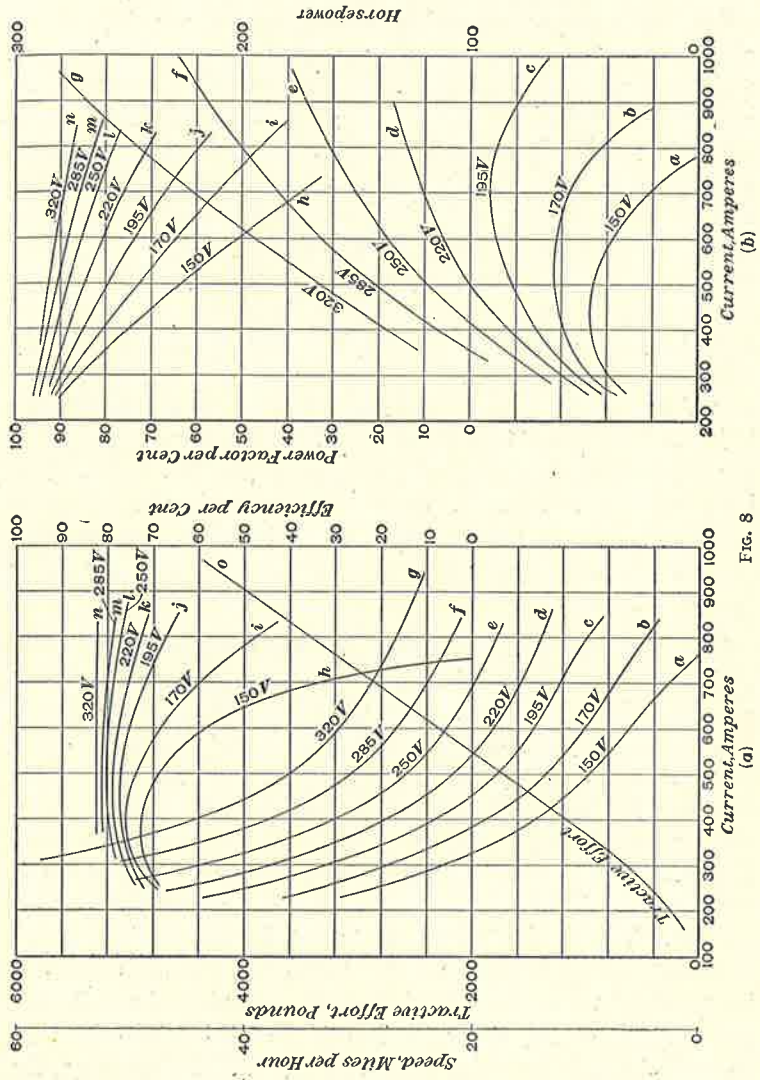

FIG. 8

various currents is given by curve o. The curves a to g in view (b) show the horsepower developed by the motor at various

voltages and currents, and the curves *h* to *n* show the power factor under similar conditions.

35. Operation on Direct Current.—When the windings of the compensating coil are connected in series with the armature and main field windings, an alternating-current series motor can be operated from a direct-current supply. All the features introduced to prevent sparking when running on alternating current are operative when the motor is running on direct current, and therefore, as the tendency to sparking is much less in the latter case the commutation is excellent. Owing to the fact that there is no E.M.F. required to overcome the reactance of the field windings when the motor is working on direct current, the whole of the counter E.M.F. has to be produced by the rotation of the armature. The speed of the motor is therefore higher with a given voltage on a direct-current supply than it is with the same voltage on an alternating-current supply if the field connections remain the same in the two cases. The losses when working on direct current are also less, and there is no power factor to be considered, so that the same output can be obtained from the motor on direct current with a smaller current input.

36. The performance curves of the same motor when run on alternating current at a frequency of 25 cycles per second, and on direct current, are shown in Fig. 9 (*a*) and (*b*), respectively. The applied voltage in each case is 250, and it will be noted that, when operating with alternating current, the highest net efficiency is 80 per cent., and when operating with direct current, the efficiency rises to 83·5 per cent. The speed curves show that for equal currents the speed is higher when the motor is operated on alternating current than when operated on direct current. This is due to the fact that for alternating-current operation the field coils on the various poles are connected in parallel, while for direct-current operation the coils are connected in series, the fields in each case being in series with the armature. With the series connection of the windings, the field flux is much greater than with the parallel connection, and hence the speed is lower.

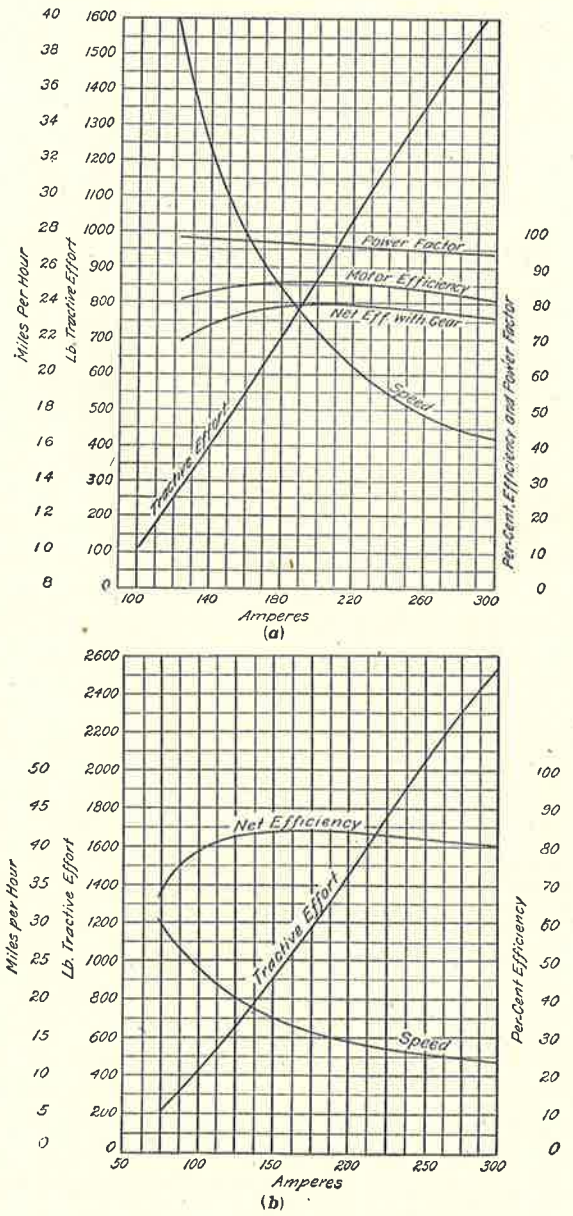

FIG. 9

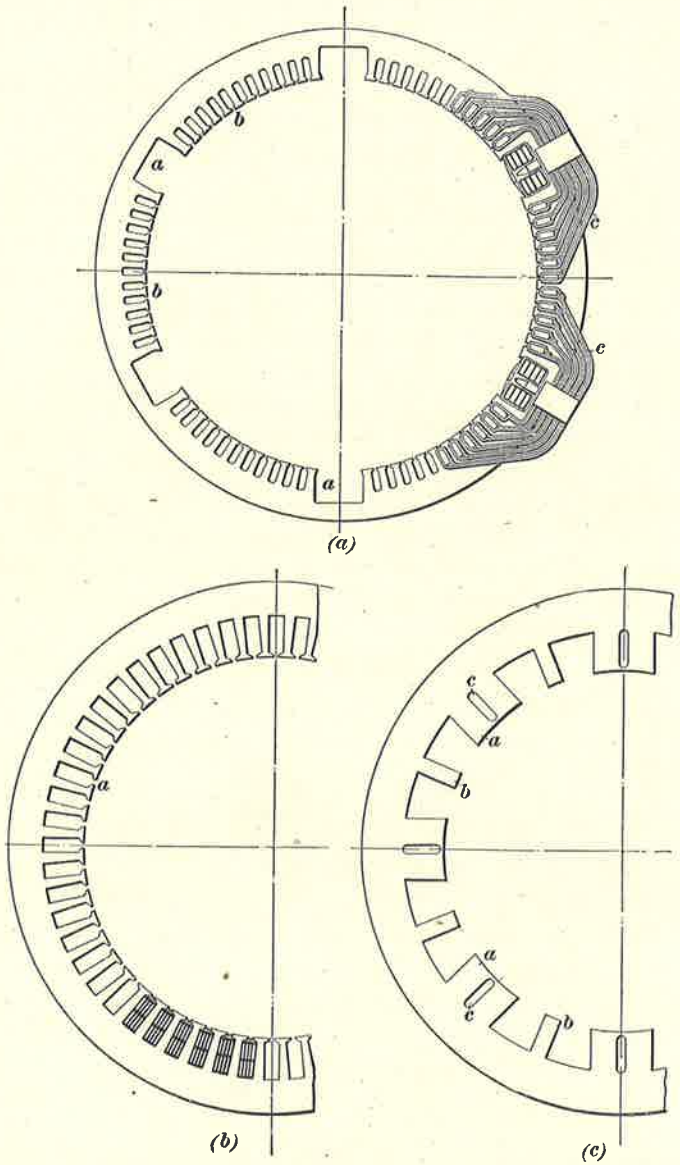

FIG. 10

CONSTRUCTION OF ALTERNATING-CURRENT SERIES MOTOR

37. Field, or Stator.—Several types of construction have been used for the **field,** or **stator,** of alternating-current series motors. One of the most common types is built up of stampings such as are shown in Fig. 10 (*a*). The main field coils are placed in the large slots *a*, the polar faces being furnished with a number of slots *b* in which are placed the compensating coils, the end connections of which are shown at *c*. Commutating poles are not used with this type of construction.

38. A stamping for a type of motor which is provided with commutating poles is shown in Fig. 10 (*b*). The stator is furnished with a number of equally spaced slots *a*, in which the windings for the main field, compensating coil, and commutating poles are placed. Each coil of the commutating-pole winding encircles only a single tooth, which is thus made the commutating pole. The centres of the main field coil and compensating coil are spaced one-half a pole pitch apart, and the centre of the commutating-pole winding coincides with that of the compensating coil. The stator laminations in both types of motor are held between end plates in a housing, in exactly the same manner as the laminations of the stator of an induction motor.

A type of field which was used when single-phase series motors were first introduced is shown in view (*c*). In this case both the main and commutating poles were formed by actual polar projections, shown at *a* and *b*, respectively, as in a direct-current machine. The compensating winding was placed in one or more slots *c* in the centres of the main polar projections. This type of construction has now been superseded by the smooth-core construction shown in view (*b*).

39. Armature.—The armatures of alternating-current series motors only differ from those used for direct-current motors and generators in that the armature conductors are often connected to the commutator segments by high-resistance leads. In some cases these leads are situated in the space between the end of the armature and the commutator. In others, the armature conductors are tapped by the high-resistance leads at the end

of the armature farthest from the commutator, and the resistance leads are taken to the commutator through the same

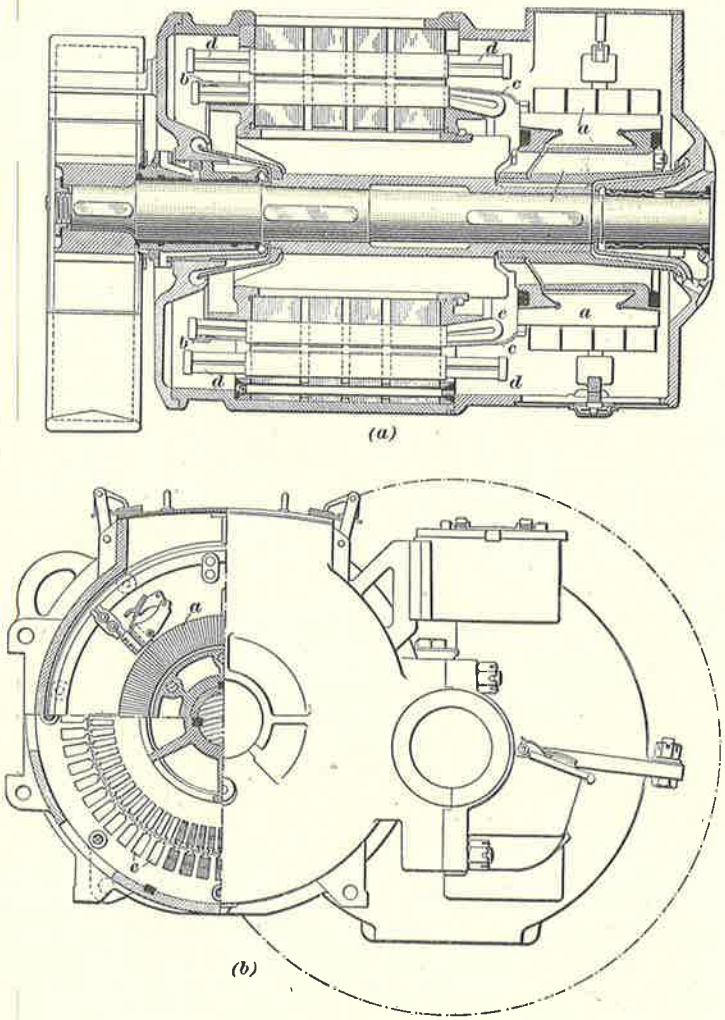

FIG. 11

slots as the armature conductors, or through separate holes in the armature core below the main slots. This enables longer

resistance leads to be used, and thus increases the resistance in circuit with the short-circuited coil during commutation. In Fig. 11 is shown the construction of a 225-horsepower railway motor, view (*a*) being a section parallel to the shaft, and (*b*) an end view and part section. The commutator *a* is connected to the armature conductors at the point *b* by the resistance leads *c*, which are placed above the ordinary conductors in the main armature slots. These resistance leads carry current only when they are in the commutating field, and therefore have practically no effect on the torque of the motor. The field windings *d* are placed in a number of equally spaced slots *e*. The bearings in this motor, as in almost all railway motors, project under the armature spider at one end and the commutator spider at the other, thus economizing space and increasing the rigidity of the armature.

40. Suspension and Driving Arrangements of Motors.—Single-phase motors are suspended and coupled up to the wheels in the same way as direct-current or three-phase motors. Fig. 12 shows

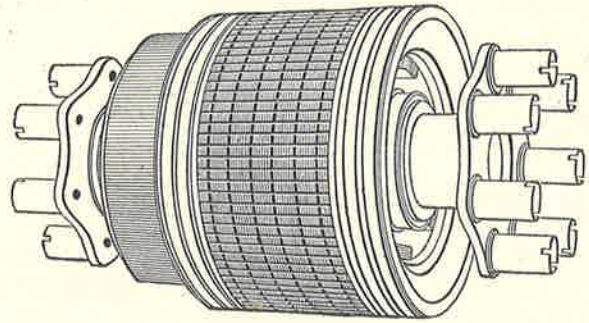

FIG. 12

the armature of a Westinghouse gearless motor for coupling direct to the track wheels. The armature is not placed directly on a shaft, but is built up on a hollow cylinder, or sleeve, through which the car axle passes. There is a clearance of about $\frac{5}{8}$ inch between the axle and the inside of the sleeve. The motor frame rests on bearings located near the rear of the armature core and the front end of the commutator spider. At each end of the

sleeve is a flange, from which project seven round hollow pins, as shown.

41. The pins shown in Fig. 12 fit into corresponding pockets in the hubs of the driving wheels, as shown in Fig. 13, which also shows the relative positions of a motor and its driving wheels. Coiled springs placed between bushes on the driving pins and bushes in the pockets take up the vibrations of the truck. The spring wound on the bush of each driving pin is so

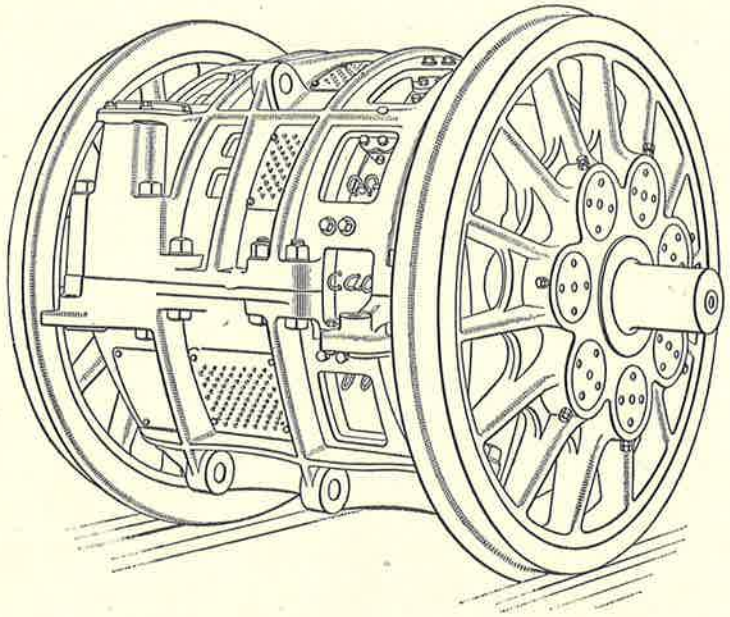

FIG. 13

constructed that it holds the pin nearly central in the recess; the end play of the motor is taken up by coiled springs, within the hollow driving pins, which press against covers in the outer ends of the pocket in the wheels. The entire weight of the motor is normally carried on springs supported from a steel frame surrounding the motor and resting on journal-boxes on the truck frame. Each motor has a normal rating of 250 horsepower for 1 hour, and a capacity of 200 horsepower for continuous working.

COMPENSATED REPULSION MOTOR

THEORY OF OPERATION

42. Points of Difference From Series Motor.—The compensated repulsion motor is so called because it is similar in principle to the ordinary repulsion motor, and because under some conditions its inductance is compensated for, so that it operates at unity power factor. In the series motor, current is conveyed to the armature by conduction, that is, the armature is connected by means of the brush leads in series with the field windings. In the compensated repulsion motor of the Winter-Eichberg type, on the other hand, current is induced in the armature coils by mutual induction from the field windings and the main motor field is produced by another current flowing in the armature superposed on the induced current.

43. Method of Connection. — The various elements of the motor in its simplest form are shown in Fig. 14. When current from the line passes through the single winding *a* on the stator, it produces a magnetic field in the direction of the arrow. This magnetic field passes through the armature *b* and, as it is an alternating field, sets up an alternating E.M.F. in the armature coils through which it passes. The coils of the armature *b* are connected in the ordinary manner to a commutator on which there are two sets of brushes *d*, *d'* and *e*, *e'*. One set *d*, *d'*, called the **exciting brushes,** is joined in series with the stator winding; the brushes of the **short-circuited** set *e*, *e'* are connected together by the connection *c*. As in the series motor, there are both speed and transformer E.M.F.'s in the armature winding.

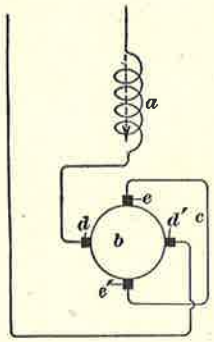

FIG. 14

The E.M.F. in any single coil will be proportional to the rate of change of the total flux passing through that coil, and as this

flux is in a definite direction, as indicated by the arrow, the E.M.F. in any particular coil will depend on the position of that coil.

44. Directions of Transformer E.M.F.'s.—The arrangement for a simple two-pole field and a ring-wound armature is shown in Fig. 15, the commutator being omitted for the sake of simplicity. At the instant under consideration, the polarity of the field is as indicated by the letters *N* and *S* due to current supplied from mains connected to terminals *h* and *g*, and is increasing in strength; the motor is supposed to be standing still. The coils *a*, *a'* have the field set up by the resultant of the stator ampere-turns and the armature ampere-turns due to the induced current, passing through them, and therefore have induced in them the full value of the transformer E.M.F. The coils *b*, *b'* are only cut by a fraction of the total flux, and therefore have only a fraction of the full E.M.F. induced in them, while coils *c*, *c'*, which lie in the same plane as the field, are not cut at all and have no E.M.F. By applying the rule in Art. **13**, it will be found that the directions of the transformer E.M.F.'s are as shown by the curved arrows. There is no E.M.F. due to transformer action across the brushes *d*, *d'*, because the effects of the sections of the winding between these brushes neutralize one another. The full transformer E.M.F. is, however, obtained across the brushes *e*, *e'*.

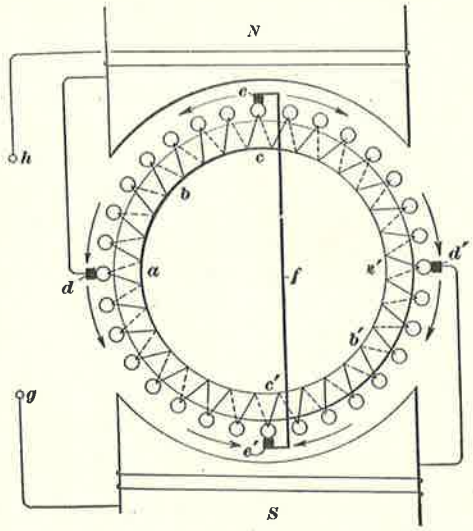

FIG. 15

45. As the full transformer E.M.F. is acting across the short-circuited brushes *e*, *e'*, Fig. 15, a current will be produced in

the closed circuit composed of the armature coils, the two brushes *e*, *e'*, and the connection *f*. A simple and useful way of considering this point is to regard an armature with its commutator as capable of producing a magnetic field, the axis of which is along the line joining the brushes through which the armature current passes. Thus, a current passing through the short-circuited brushes *e*, *e'* will tend to produce a magnetic field with a vertical axis, and a current through the exciting brushes *d*, *d'* will tend to produce a magnetic field with a horizontal axis. Two currents entering the armature simultaneously by the two brush sets will produce a resultant field which may be considered as being made up of two independent magnetic fields along the two perpendicular axes, the strength of each being proportional to the current producing it, neglecting magnetic saturation of the iron parts of the motor. Considering the armature in this way, the closed circuit completed by the brushes *e*, *e'* and the connection *f* may be regarded as the secondary winding of a transformer of which the field coils are the primary, and the *vector diagram* showing the relations of the magnetic field, the transformer E.M.F., and the currents in these two circuits can be drawn exactly in the same way as for a static transformer, provided the motor is not running.

46. Production of Torque.—In Fig. 15 it is shown that the induced current in the armature coils between brushes *e* and *d* is in an opposite direction to that between brushes *e* and *d'*. Similarly, the currents in the circuits *e' d* and *e' d'* are in opposite directions. Hence, there can be no resultant torque due to the interaction between the currents in the armature and the magnetic field produced by the stator coil, as the force produced by the current in any one conductor is neutralized by the force due to the current in another conductor. If, however, a magnetic field is provided, the axis of which is at right angles to the field due to the stator coil, there will be a definite torque due to the action of this field on the armature conductors carrying current if this field and the armature current are not 90° out of phase. This is the actual method whereby the torque of the compensated repulsion motor is produced, the magnetic field

which gives the torque reaction being provided by means of the current, called the exciting current, entering and leaving the armature by the exciting brushes d, d'.

To summarize, a current which enters and leaves by means of the short-circuited brushes e, e' is induced in the armature, and a magnetic field is produced by an exciting current entering and leaving the armature through the exciting brushes d, d', and this field reacting on the induced armature current produces the torque of the motor. The exciting field, with an axis through d, d', which is set up by the exciting current also gives rise to transformer and speed E.M.F.'s. These manifest themselves at 90 electrical degrees to the transformer and speed E.M.F.'s due to the first field; that is, the transformer E.M.F. due to the exciting field is operative at the exciting brushes d, d', and the speed E.M.F. due to the exciting field is at the short-circuited brushes e, e'.

VOLTAGE AND CURRENT RELATIONS IN COMPENSATED REPULSION MOTOR

47. Voltage and Current Relations at Starting.—The phase relations of the currents and pressures in the windings of a compensated repulsion motor at starting are given by the vector diagram, Fig. 16. The current in the stator windings, that is, the primary current, is represented by the line $O\,a$. This primary current also flows through the armature windings, by means of the exciting brushes, and acts as an exciting current in the armature windings. The primary current therefore sets up a magnetic

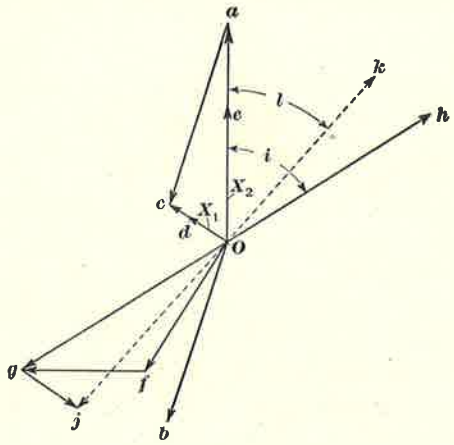

FIG. 16

field X_2, which is represented on the diagram by the line $O\,e$. A large induced current circulates in the armature windings through the short-circuited brushes and is nearly opposite in phase to the primary current $O\,a$, so that the line $O\,b$ represents the induced or secondary current. The magnetic field X_1, which causes the secondary current $O\,b$ to flow, is due to the resultant ampere-turns of the primary current in the stator coil and the secondary current in the armature. The field is represented on the diagram by the line $O\,d$, and is produced by the equivalent current $O\,c$, which is the resultant of the primary current $O\,a$ and the secondary current $O\,b$.

48. The alternation of the field X_1, Fig. 16, sets up an induced or transformer E.M.F. E_1 in the stator coil and this E.M.F. is represented by line $O\,f$ at right angles to $O\,d$. The field X_1 also produces a transformer E.M.F. in the armature windings between the short-circuited brushes. This E.M.F. is in phase with the E.M.F. E_1 and causes the flow of the secondary current $O\,b$. The alternation of the field X_2 induces an E.M.F. E_2 between the exciting brushes of the armature. The E.M.F. E_2 is represented on the diagram by the line $f\,g$, at right angles to $O\,e$, and tends to cause the primary current $O\,a$ to lag behind the impressed E.M.F., $O\,h$. The impressed E.M.F. must be equal and opposite to the resultant $O\,g$ of $O\,f$ and $f\,g$.

49. Effect of Speed E.M.F.'s When Running.—When the armature of a compensated repulsion motor begins to rotate, a speed E.M.F. due to the conductors cutting the lines of force of the exciting field X_2, Fig. 16, is developed between the short-circuited brushes. This E.M.F. is in phase with the field X_2 and more or less directly opposes the transformer E.M.F. which causes the secondary current to flow, the resultant voltage being just sufficient to force the secondary current through the circuit against the impedance of the windings. A speed E.M.F. is also generated in the armature by the conductors cutting the flux of field X_1. This E.M.F. is between the exciting brushes and is therefore in the primary circuit of the motor. The speed E.M.F. is in phase with the field X_1 and is represented on the diagram by the line $g\,j$, which shows that the E.M.F. is acting

from g toward j, thus more or less completely neutralizing the transformer E.M.F. $f\,g$. The effect of this neutralizing action is to bring the resultant pressure from line $O\,g$ to $O\,j$. The impressed pressure will thus be brought from the position $O\,h$ to the position $O\,k$. The angle of lag of the current $O\,a$ is reduced from the angle i to the angle l, thus improving the power factor of the motor. As the speed is increased the speed E.M.F.'s will increase, and at a certain speed the impressed pressure may be brought into phase with the primary current and the power factor made unity. If the speed is further increased a leading current may be obtained, but when this condition is obtained there is usually a certain amount of sparking. The motor is commonly run at a speed somewhat less than that required to give unity power factor.

COMMUTATION OF REPULSION MOTOR

50. Commutation at Brushes Carrying Induced Armature Current.—The commutation at the short-circuited brushes carrying the induced current must be considered separately from the commutation at the brushes which carry the exciting current. In the coils short-circuited by the main brushes there is a speed E.M.F. due to the conductors moving in the main field of the motor, a transformer E.M.F. due to the alternation of the exciting field set up by the armature, and a reactance voltage due to the reversal of the induced current as the commutator segments pass under the brushes. The resultant E.M.F. must be kept small or partially neutralized by a commutating field of the proper strength and direction in order to avoid violent sparking. The resultant E.M.F. cannot easily be completely neutralized, because the speed E.M.F. varies with the speed and the reactance voltage varies with both speed and load, while the commutating field is usually made to vary only with the load.

51. Commutation at Brushes Carrying Exciting Current.—As the exciting current supplied to the armature of a compensated repulsion motor is small compared with the induced current, there is comparatively little trouble due to sparking. The transformer E.M.F. in the short-circuited coil is not excessive, as the

field set up by the stator winding is much less than the field due to the exciting current. The speed E.M.F. due to the coils short-circuited by the exciting brushes cutting lines of force of the exciting field may be fairly large, but is more or less completely neutralized by the transformer E.M.F. due to the stator field. In practice, no difficulty due to sparking at the exciting brushes has been encountered.

SPEED REGULATION OF REPULSION MOTOR

52. Theory of Speed Variation.—The compensated repulsion motor may be controlled in the same way as a single-phase series motor, that is, by varying the applied terminal voltage by means of a variable ratio transformer, or in any other convenient manner. In practice, however, it is usual to employ a series transformer to supply the magnetizing current for the armature, as shown in Fig. 17. The stator coil a is connected to the primary winding f of a series transformer, the secondary g of which is connected to the brushes d, d'. The series transformer can be made with any desired ratio between the primary and secondary turns, or it may be made with a variable ratio by providing the secondary with a number of tappings h. At starting, the pressure across the exciting brushes d, d' is made high in comparison with the pressure across the motor terminals. A strong exciting field will be produced, and therefore a low speed will give a speed E.M.F. great enough to limit the induced current due to the main field in the circuit $c\ e\ e'$. The speed of the motor may be increased by increasing the E.M.F. applied to the main terminals. This increase in applied E.M.F. will cause the main current and therefore the induced current to increase. If the exciting field remains constant, the torque will increase and thus increase the speed. If the exciting field is weakened, the speed E.M.F. opposing the flow of induced current will be decreased and the

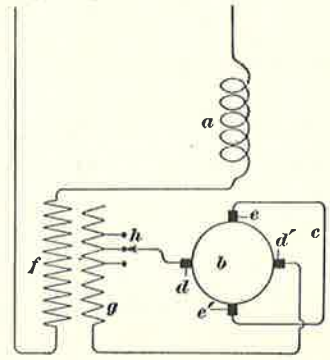

FIG. 17

induced current will increase until the speed E.M.F. again comes up to its normal value due to increase of speed.

53. Arrangement of Connections for Speed Control.—In the most modern arrangements an autotransformer *d*, Fig. 18, is used to supply the exciting current to the armature *a*. The exciting current can be adjusted to suit the running or starting conditions by closing different contactors *e*. The main field *b* and the commutating field *c* are connected in series, but the phase relation of the commutating field may be changed to suit the usual running conditions by closing contactor *f*. The pressure applied to the motor is controlled by contactors *h* connected to consecutive tappings on the secondary of the main transformer *g*. The primary of the transformer *g* is supplied with current at high pressure from the trolley wire, and this is stepped down to a pressure suitable for the motors. The highest pressure applied to the motor terminals is about 750 volts.

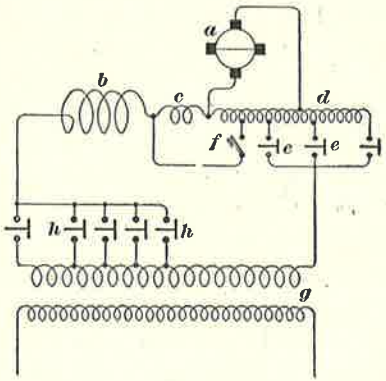

FIG. 18

54. Theoretically, there is no reason why the stator winding of a compensated repulsion motor should not be wound for direct connection to the high-tension trolley wire, the only current transformed being that required for the exciting circuit on the armature. In practice, however, on account of the increased cost of upkeep due to having a high voltage on the motors, it is usual to install a step-down transformer, as shown in Fig. 18.

CHARACTERISTIC CURVES OF REPULSION MOTORS

55. Tractive-Effort, Speed, Efficiency, and Power-Factor Curves.—The compensated repulsion motor fulfils the requirement of a good traction motor in that it is capable of giving a

large starting torque. Its characteristic curves much resemble those of the series motor, in that the torque increases and the speed decreases rapidly as the load becomes greater. In Fig. 19 are shown the curves for a 6,000-volt 25-cycle motor, the control of which is effected by varying the transformation ratio of the

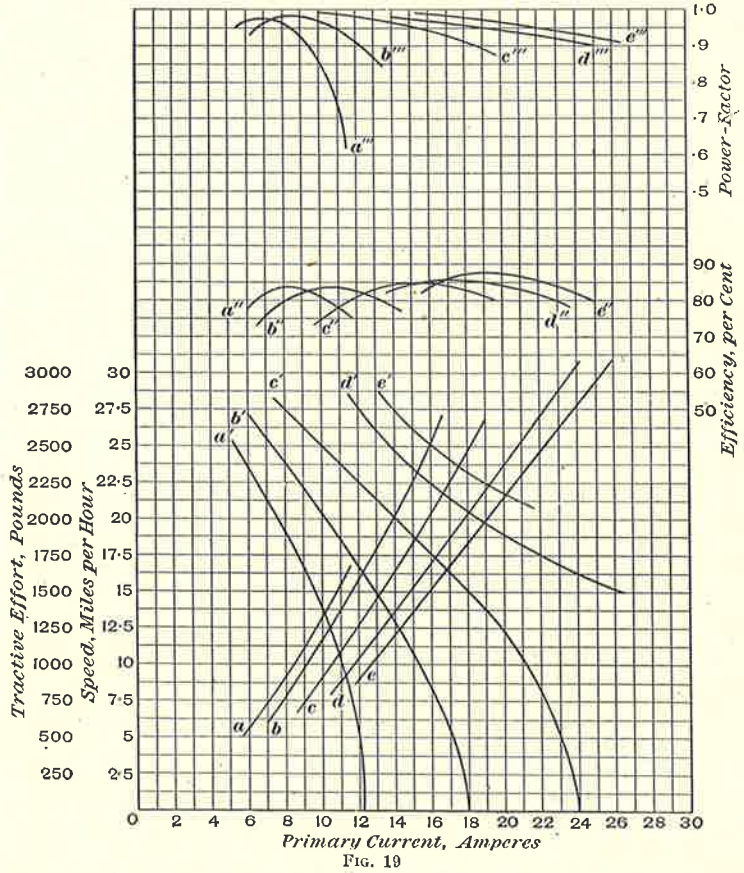

FIG. 19

step-down transformer in the supply circuit. Curves *a*, *b*, *c*, *d*, *e* show how the tractive effort, in pounds, exerted by the locomotive carrying the motor varies with the primary current for different pressures applied to the motor terminals. The corresponding curves of speed, in miles per hour, are shown

at a', b', c', d', e'. The efficiencies of the motor at different loads and with the various applied pressures are given by the curves a'', b'', c'', d'', e'', the loss due to the exciting transformer being included with the motor losses. The way in which the power factor varies with the load for various ratios is shown by the curves a''', b''', c''', d''', e'''; these show that, by changing

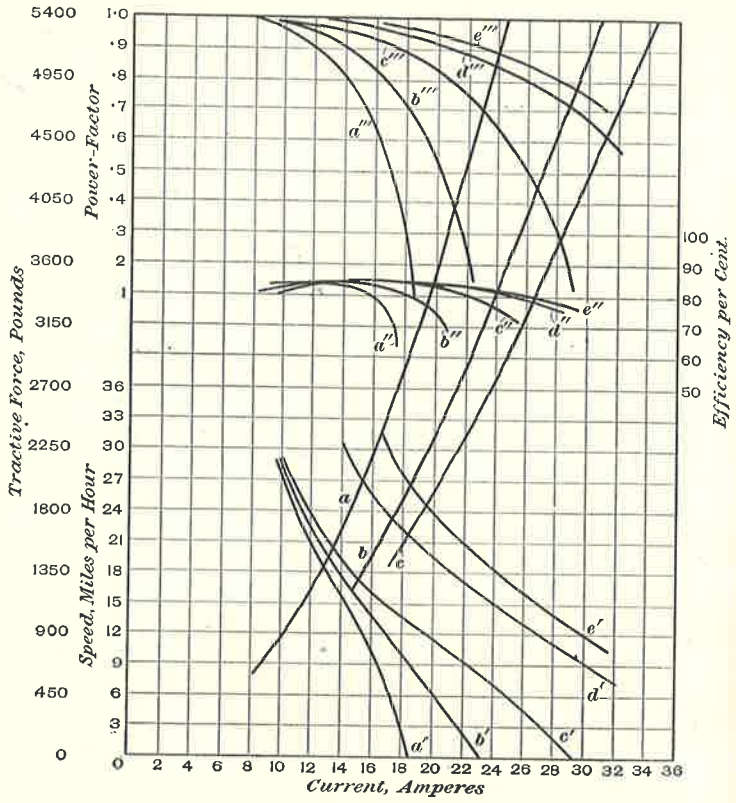

FIG. 20

the ratio at the right moment when starting, and using the correct ratio when running, the power factor can be kept very near unity.

56. Curves for 200-Horsepower Motor.—The curves for a railway motor with a rated capacity of 200 horsepower are given in

Fig. 20. The current is supplied at a pressure of 750 volts and a frequency of 25 cycles per second from the secondary of a step-down transformer, the primary of which is connected to the 6,000-volt overhead line. The relations between tractive effort and primary current for three positions of the controller are shown by the curves a, b, and c, the pull being measured at the tread of a driving wheel 39·375 inches in diameter. The speeds of the locomotive containing the motor are plotted against the primary current for five positions of the controller in curves a', b', c', d', and e'. The efficiencies are given by the curves a'', b'', c'', d'', and e'', and it should be noted that the efficiencies reach a maximum of 85 per cent., although all the losses in the main step-down transformer, the exciting transformer, the motor, and the gearing are taken into account. The power factors for the five controller positions are given by the curves a''', b''', c''', d''', and e'''.

CONSTRUCTION OF REPULSION MOTOR

57. Stator.—The construction of the stator of a six-pole compensated repulsion motor is shown in Fig. 21. The stator core a is built up of laminations, and is contained in a cast-iron stator housing b. The main field winding c consists of three coils per pole, and the commutation winding d is made of single coil, surrounding small sections at the centres of alternate poles. The effect of the commutating poles placed as shown is the same as though the windings were placed on every pole and each consisted of half as many turns.

58. Armature.—The armature corresponding to the stator just described is shown in Fig. 22. The winding is of the ordinary type used for direct current and consists of copper bars bent to shape and held in place in the partly closed slots by the insertion of wooden wedges. For purposes of ventilation, one end of the armature is provided with a centrifugal fan a, which communicates through ventilating ducts in the armature core and commutator spider with the apertures b. When the armature is revolving, air is expelled from the fan a and drawn

in at *b*, thus maintaining an air circulation which effectually cools the motor. The end connections to the commutator *c* are

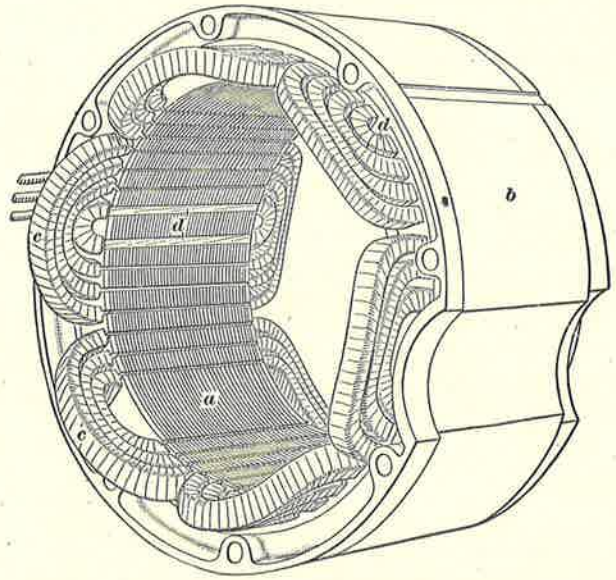

FIG. 21

covered in by a cap *d*, in order to prevent the accumulation of dust.

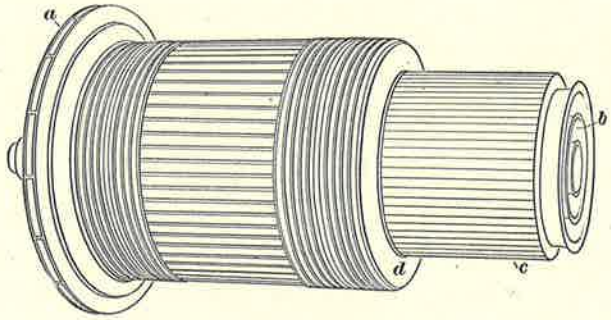

FIG. 22

59. The complete motor is illustrated in Fig. 23. The centrifugal fan *a* runs in an opening between the gear-case *b* and the

main housing *c* of the motor. The cast-iron housing is provided with a lug *d*, through which pass the bolts for attaching the motor to the truck of the locomotive or motor coach. The brush gear is totally enclosed in the case *e*, which is provided

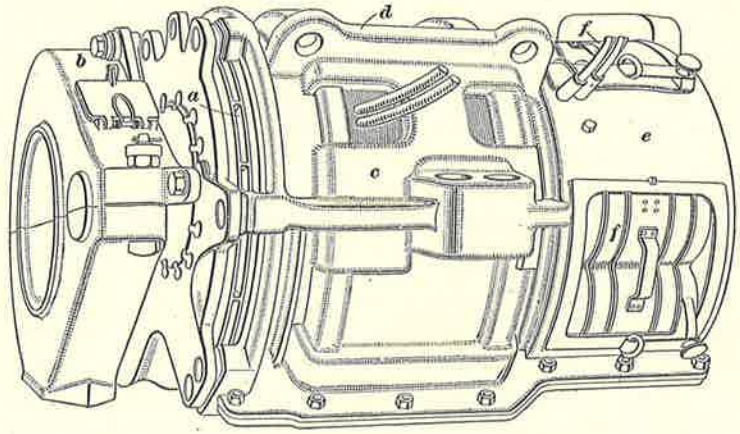

FIG. 23

with doors *f* for inspection purposes. The whole motor is very substantially constructed in order to withstand the severe vibration and shocks inseparable from railway work.

SYSTEMS OF MOTOR CONTROL

GENERAL PRINCIPLES

60. Control by Variation of Voltage.—Speed control of the single-phase railway motor is obtained by varying the voltage at its terminals, the same as with direct-current motors. Where alternating current is used, however, this can be done much more easily and economically than with direct current. Instead of first connecting the motors in series and then in parallel and using a variable resistance in the circuit with each grouping, as is done with direct-current motors, it is merely necessary to connect the alternating-current motors to different tappings on

the transformer or autotransformer. This is accomplished in small equipments, where single-car operation only is desired, by means of drum-type controllers that are similar in general appearance to those used with direct-current motors. In large equipments, or where multiple-unit train operation is desired, essentially the same connections are made by means of unit switches operated by compressed air from the air-brake system and controlled by electromagnetic valves, or by means of contactors operated by low-tension single-phase current and controlled directly from the master controller. The action of the magnet valves in the compressed-air system is regulated by a master controller, and current for operating them is generally supplied by a small 14-volt storage battery on the car.

61. Two- and Four-Motor Equipments.—When a car equipment consists of only two series motors, they are connected in parallel, so that in case of damage to either motor it may be cut out of circuit without interfering with the operation of the other. Where the equipment consists of four series motors, however, they are connected two in series, and these two groups are connected in parallel. In case of damage to one motor of a four-motor equipment, the pair of motors to which it belongs is cut out. This arrangement is used to reduce the cost of controllers, switches, wiring, etc., which, within the limits ordinarily used, depends on the current to be handled rather than on the voltage. Thus, the same controller or switch group is used with a given size of motor, whether the equipment consists of two or four motors.

62. Preventive Reactance Coil.—In the method of voltage variation by means of tappings on a transformer or autotransformer, it is necessary to be able to change from one voltage to another without breaking the main circuit. If this is done by means of a sliding contact, which makes contact with a new tapping at a higher or lower voltage before it leaves the old one, the section of the winding between the two tappings is short-circuited by the contact. In order to avoid this, choking coils, known as **preventive reactance coils,** are employed ; these are connected as shown in Fig. 24. In view (*a*) the ends of

the preventive reactance coil *a* are shown connected to the tappings *c*, *d* of the autotransformer *b*, the middle point of the reactance coil being connected to the motor circuit. This connection is obtained when the controller is on the first notch

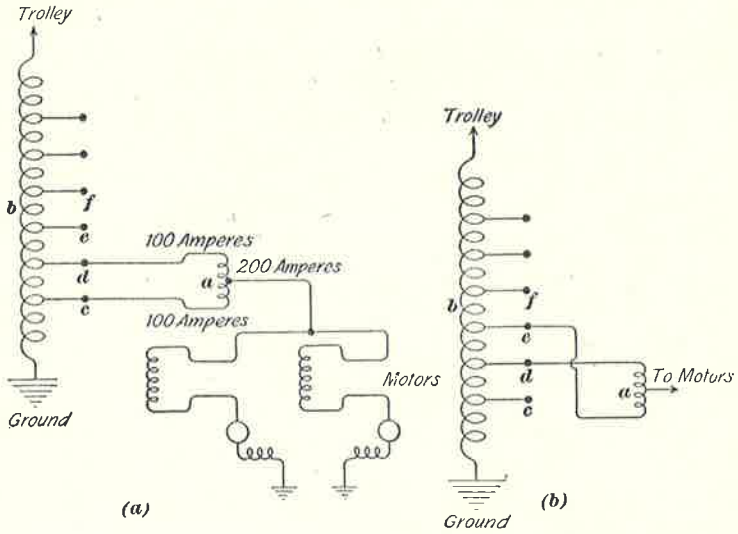

FIG. 24

and gives a low voltage to the motors. If the motors require 200 amperes, then 100 amperes flows through each of the tappings.

63. In order to increase the voltage applied to the motors the controller is moved to the second notch, and the lower end of the preventive coil *a*, Fig. 24 (*b*), is then disconnected from tapping *c* and connected to tapping *e* of the autotransformer *b*. The supply to the motors is not interrupted during the change, because the connection to tapping *d* is not broken. In order to raise the voltage another step, the connection to tapping *d* will be transferred to tapping *f*, leaving the connection to tapping *e* untouched. In addition to preventing the short-circuiting of transformer sections, the use of the preventive coil splits up the current taken by the motors into two parts, so that the contactors

used for making connection to the tappings need only be capable of dealing with half the motor current. In cases where very heavy currents are to be handled, and a gradual voltage variation is required, three preventive coils may be used, as shown in Fig. 25, in which the method of gradually increasing the voltage by changing the connections one at a time is shown. In this case the total current is divided among four contacts.

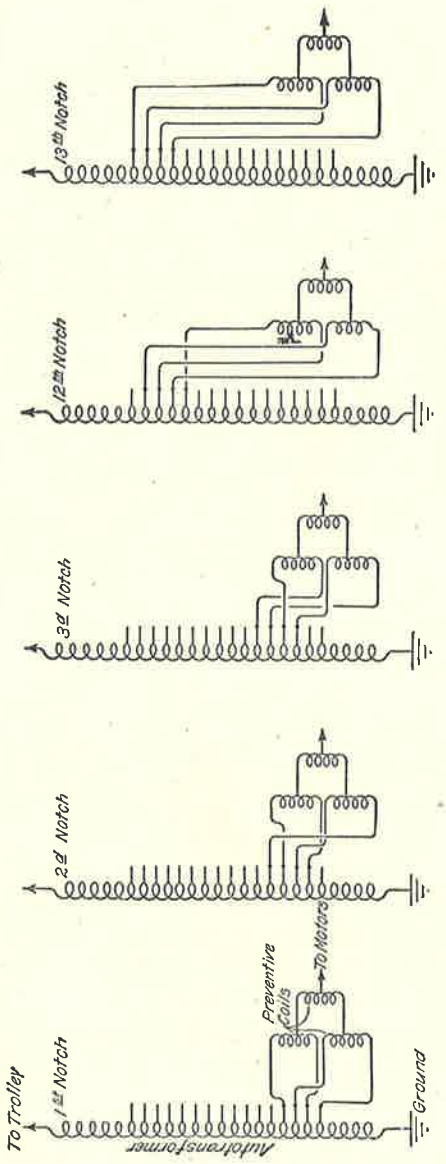

FIG. 25

64. Preventive Resistance. — For use in connection with drum-type controllers, a non-inductive resistance, called a **preventive resistance,** is connected in parallel with the preventive reactance coil, to reduce the sparking that may occur when breaking a tapping contact. Each half of the preventive reactance coil is bridged by one-half of the resistance. When one of the tapping

contacts is broken, the current suddenly decreases in one-half

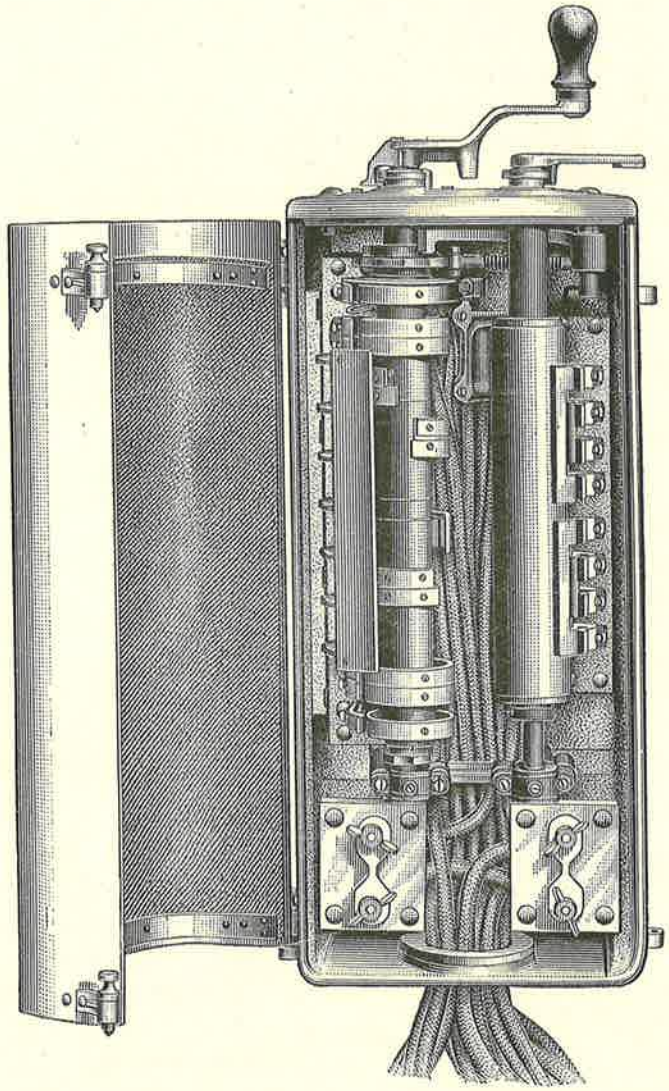

FIG. 26

of the reactance coil. This sets up a high E.M.F. due to the

inductance, and might cause sparking at the contact if it were not for the portion of the resistance through which the reactance coil may discharge and thus allow the current and the magnetic field to decrease in strength slowly. The preventive resistance is so proportioned that there is very little loss in it, and, in order to simplify the controller connections, it is left in circuit for all positions of the controller, except the last, where it can be cut out without adding complication. On account of the greater current-breaking capacity of unit switches, this resistance is not required where they are used.

65. Operation on Direct Current. — On some railways in America and on the Continent it is necessary to operate the equipment on direct current as well as on alternating current, in which case series motors must be used. The direct-current operation is generally through cities or towns, where the speed is necessarily limited, while the alternating-current operation is in the open country, where a high speed is usually desirable. The single-phase series motor will operate somewhat faster on direct current than it will on alternating current of the same voltage. If, therefore, two 250-volt alternating-current motors geared for the proper alternating-current speed are operated in series from a 500-volt direct-current trolley system, the speed will usually be very much higher than is required. On this account, equipments for operation on both alternating and direct current are usually provided with four motors. These motors are operated two in series in the ordinary way on alternating current, but are connected all four in series on direct current. With this arrangement, the speed of a car with normal direct-current voltage on the trolley is about two-thirds of that with normal alternating-current voltage. When operating on direct current, the motors are controlled in the ordinary way by means of a resistance in series with them.

DIRECT CONTROL FOR SERIES MOTORS

66. Controller. — A Westinghouse controller suitable for directly controlling two or four 50-horsepower series alternating-current motors is shown in Fig. 26. In general appearance this

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controller is similar to a controller for direct-current operation. It contains a main power drum for connecting the various autotransformer tappings to the motor circuit, and a reverse drum for reversing the direction of rotation of the motor armatures. Fig. 27 shows the preventive reactance coil, and Fig. 28 the preventive resistance, used in connection with this controller.

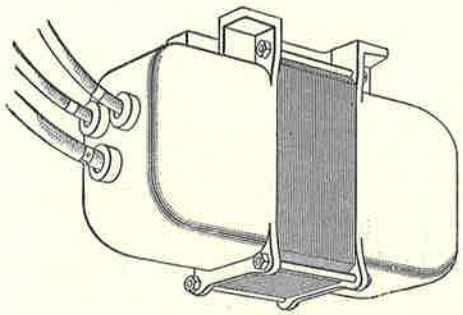


FIG. 27

67. Controller-Wiring Diagram. — An autotransformer with six secondary tappings and the wiring diagram of a hand controller arranged for connecting the several autotransformer tappings to the motor circuit is shown in Fig 29. The tappings

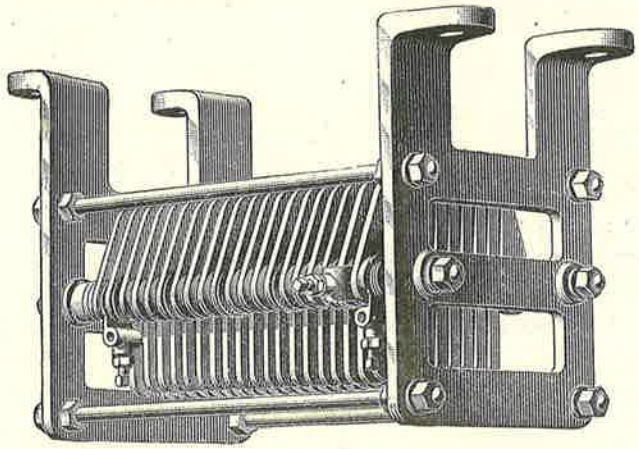


FIG. 28

provide E.M.F.'s of 160, 190, 220, 250, 280, and 310 volts. The E.M.F.'s impressed on the motor terminals differ slightly from these values, owing to the action of the preventive reactance coil. The motor circuits receive current from the middle

points of the preventive reactance coil and the preventive resistance, across which an E.M.F. of 30 volts is impressed.

68. When the controller, Fig. 29, is on the *first notch*, the contact fingers are in the position indicated by the dotted line *1* and fingers R_1 and C_1 are connected with finger L_2 (the 190-volt tapping), and fingers C_2 and R_2 are connected with finger L_1 (the 160-volt tapping). As R_1 and R_2 are the terminals of the preventive resistance, and C_1 and C_2 are the terminals of the preventive reactance coil, the E.M.F. impressed on the coils is 190 volts − 160 volts = 30 volts, and the E.M.F. at the middle

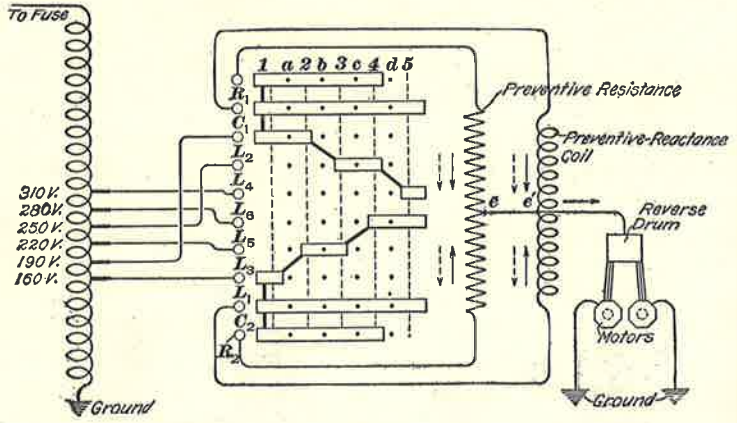


FIG. 29

points e, e' of the coils is 15 volts higher than the lower value and 15 volts lower than the higher value, or 175 volts. The E.M.F. of 30 volts forces currents through the resistance and the reactance coil independently of the operation of the motors. The directions of these currents are from the tapping that is, at a given instant, of a higher potential to the tapping that, at the same instant, is of a lower potential. The current therefore alternates through the coils.

69. First Notch.—If the trolley wire is positive at a certain instant and the controller is on notch *1*, Fig. 29, L_2 is at a higher potential than L_1, and the E.M.F. of 30 volts tends to send currents through the preventive coils in the directions indicated by the dotted arrows. If the motor circuit is also active, the

currents from L_2 and L_1 flow to e and e' through the coils in the direction indicated by the full-line arrows. The motor currents in each half of a coil are in opposite directions and of nearly equal value. The currents join and flow to the motor circuit at the middle point of the coils. Where the normal exciting current of a coil and the motor current oppose each other, the motor current predominates and determines the direction of flow. At the particular instant under discussion, motor currents flow from the 190-volt tapping L_2 to e and e', and from the 160-volt tapping L_1 to e and e', there being an E.M.F. of approximately 175 volts impressed on the motor circuit.

70. Second Notch.—When the controller is passing from the first to the second notch, finger L_1, Fig. 29, drops contact with its drum segment, while finger L_2 still remains in contact with its drum segment. Current then flows through the upper portions only of the preventive coils and to the motor circuit from the 190-volt tapping. The intermediate positions of the fingers are indicated by the dots under the letters *a*, *b*, *c*, and *d*. On the second notch, R_2 and C_2 are connected with finger L_3 (the 220-volt tapping), and R_1 and C_1 are still connected with L_2 (the 190-volt tapping). The impressed E.M.F. on the motor circuit is now 205 volts. At the intermediate position *b*, finger L_3 remains in contact with its drum segment, but finger L_2 drops contact with its segment. Therefore, current flows from the 220-volt tapping only.

71. Third Notch.—On notch *3*, fingers L_4 and L_3 are active, and the E.M.F. impressed on the motor circuit is 235 volts. At the intermediate position *c*, finger L_4 remains in contact with its drum segment, but finger L_3 drops contact with its segment. Current now flows from the 250-volt tapping only.

72. Fourth Notch.—On notch *4*, fingers L_5 and L_4 are in service, and the E.M.F. impressed on the motor circuit is 265 volts. As fingers R_1 and R_2 drop contact with their drum segments at intermediate position *d*, the preventive resistance is cut out of circuit. Finger L_5 and the lower half of the reactance coil are alone active at this point, and current now flows from the 280-volt tapping to the motors.

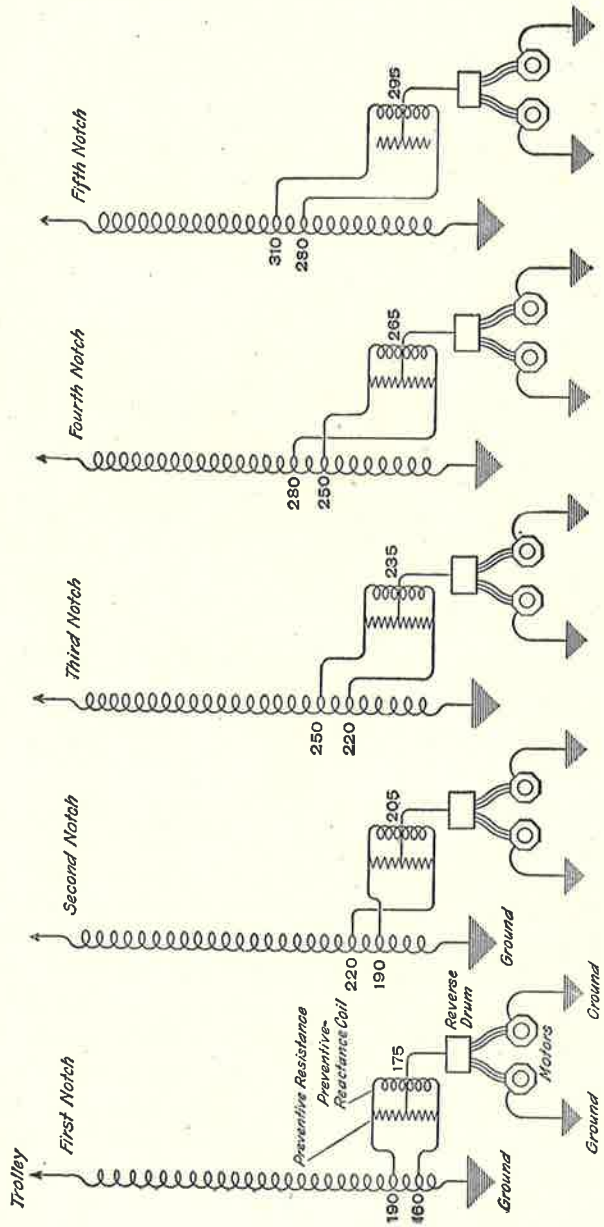

Trolley
First Notch
Second Notch
Third Notch
Fourth Notch
Fifth Notch
Preventive Resistance
Preventive-Reactance Coil
Reverse Drum
Motors
Ground
Ground
Ground
Ground
190
160
175
220
190
205
250
220
235
280
250
265
310
280
295

Fig. 30

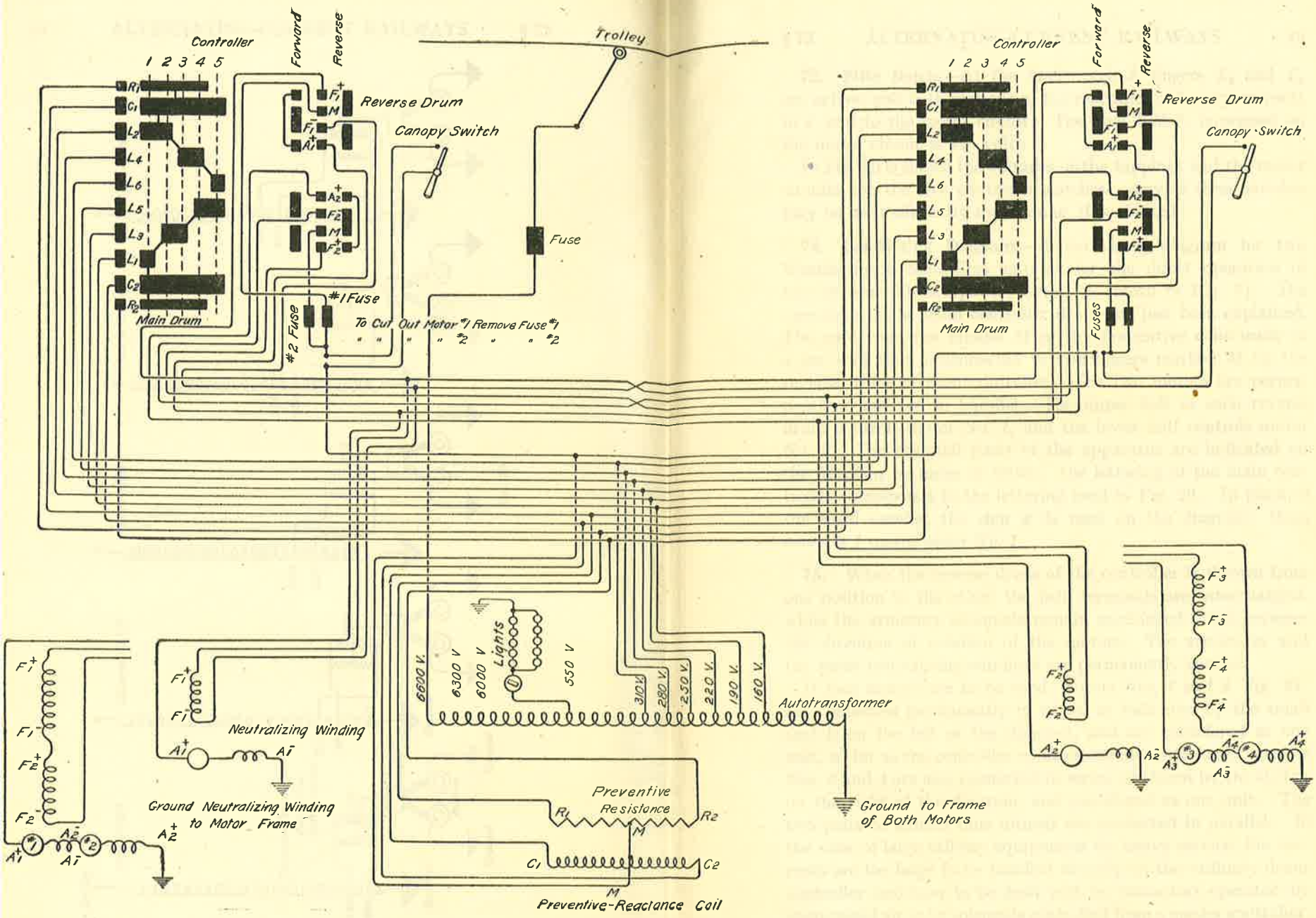

Controller
1 2 3 4 5
Forward
Reverse
Trolley
Reverse Drum
Canopy Switch
Fuse
#1 Fuse
#2 Fuse
To Cut Out Motor #1 Remove Fuse #1
" " " " #2 " " #2
Main Drum
Fuses
Lights
6600 V.
6300 V
6000 V
550 V
310 V.
280 V.
250 V.
220 V.
190 V.
160 V.
Autotransformer
Neutralizing Winding
Ground Neutralizing Winding to Motor Frame
Ground to Frame of Both Motors
Preventive Resistance
Preventive-Reactance Coil

Fig. 31

73. Fifth Notch.—At the final notch *5*, fingers L_6 and L_5 are active, and both sections of the reactance coil carry currents to e' and to the motor circuit. The final E.M.F. impressed on the motor circuit is 295 volts.

In Fig. 30 is shown the voltages of the tappings and the motor circuits for the five controller notches. Any of these notches may be used efficiently for running, if so desired.

74. Car-Wiring Diagram.—A car-wiring diagram for two Westinghouse controllers suitable for the direct operation of two or four 50-horsepower motors is shown in Fig. 31. The operation of the main controller drum has just been explained. The wire from the middle M of the preventive coils leads to a car wire that is connected to two fingers marked M on the reverse drum of each controller. The two motors are permanently connected in parallel. The upper half of each reverse drum controls motor No. *1*, and the lower half controls motor No. *2*. The essential parts of the apparatus are indicated on the diagram by name or letter; the lettering of the main controller corresponds to the lettering used in Fig. 29. In place of the word *number*, the sign # is used on the diagram; thus, *motor # 1* means *motor No. 1*.

75. When the reverse drum of the controller is thrown from one position to the other, the field terminals are interchanged, while the armature terminals remain unchanged; this reverses the direction of rotation of the motors. The armatures and the series neutralizing windings are permanently earthed.

If four motors are to be used, motors Nos. *1* and *2*, Fig. 31, are connected permanently in series, as indicated by the small sketch on the left of the diagram, and are considered as one unit, so far as the controller connections are concerned. Motors Nos. *3* and *4* are also connected in series, as shown by the sketch on the right of the diagram, and considered as one unit. The two pairs of motors thus formed are connected in parallel. In the case of large railway equipments for heavy service, the currents are too large to be handled directly on the ordinary drum controller, and have to be dealt with by contactors operated by compressed air or by solenoids controlled from a master controller.

WESTINGHOUSE ALTERNATING-CURRENT UNIT-SWITCH CONTROL

76. Master Controller.—The controlling apparatus used with the Westinghouse unit-switch alternating-current control system is, in general, similar to that employed in the Westinghouse unit-switch control systems arranged for direct-current motors.

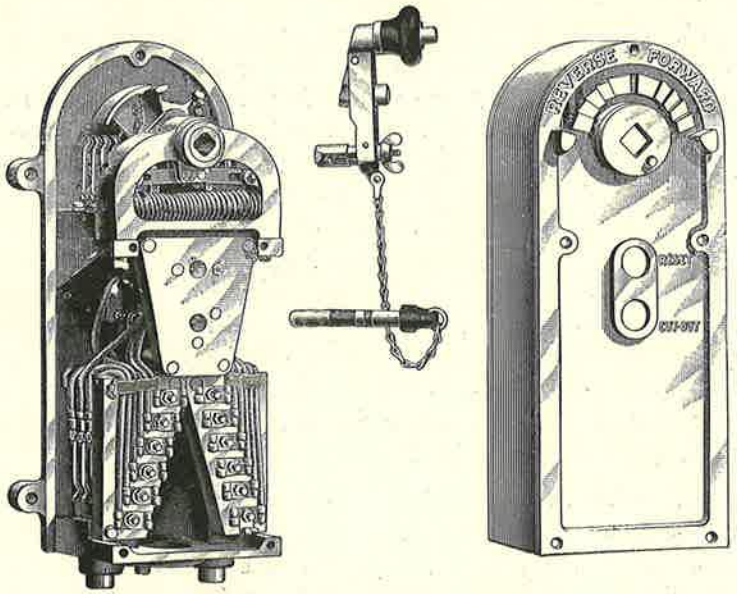


FIG. 32

A small storage battery furnishes the direct current for the control circuits in both systems. A view of a master controller for an alternating-current equipment of two or four motors is shown in Fig. 32. The controller is small, as it carries only sufficient current to actuate the control apparatus.

77. Diagram of Connections.—A car-wiring diagram for a unit-switch group and two 100-horsepower motors is shown in Fig. 33. For a four-motor equipment of the same size of motors, operating on a 3,300-volt circuit, the connections are essentially the same. In the latter case, however, the motors are connected two in series. With a four-motor equipment of such

motors, on a 6,600-volt circuit, a circuit-breaker is used in the high-tension circuit instead of a fuse.

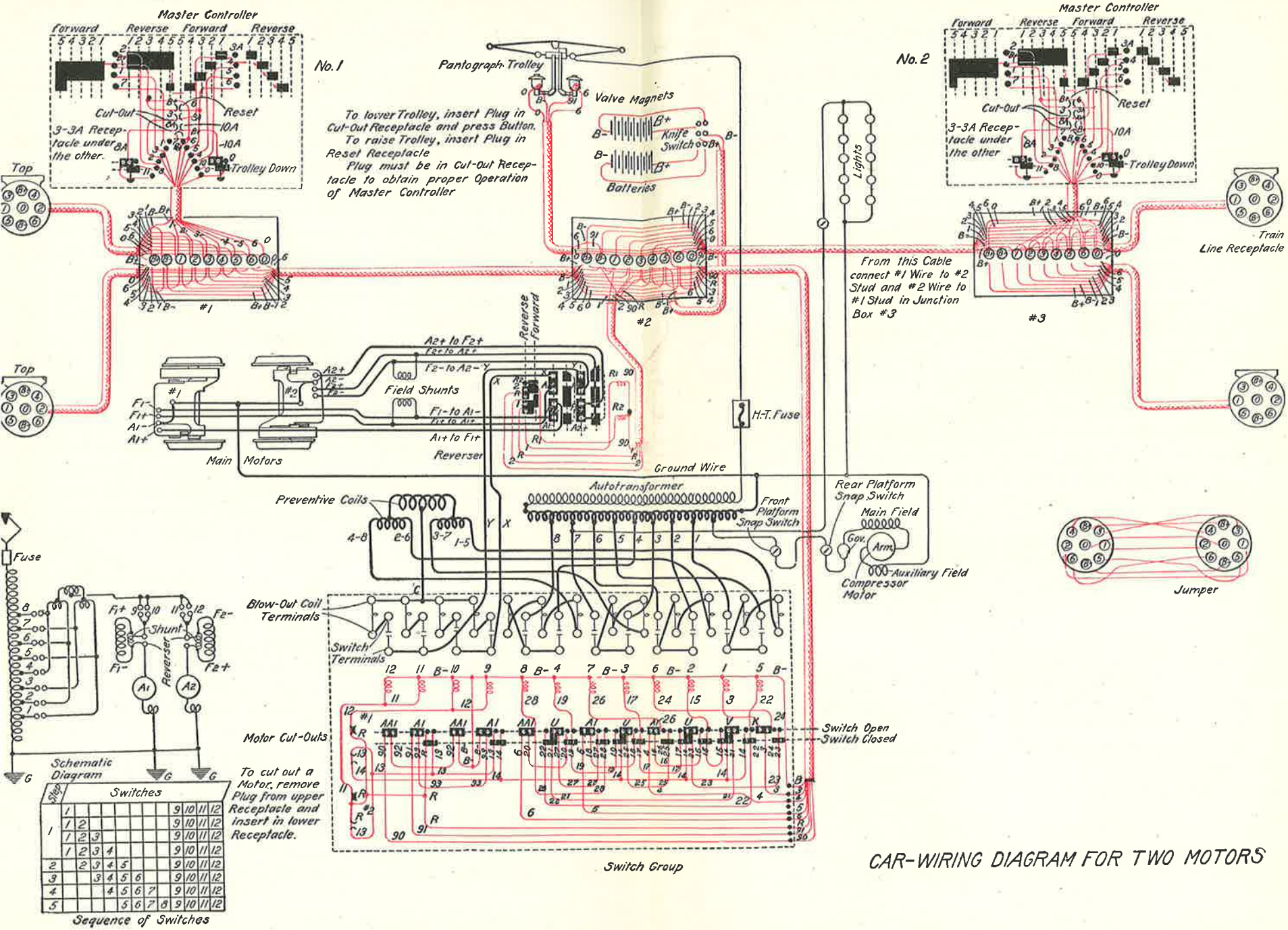
78. Operation of Current Collector.—The *pantograph* type of current collector is indicated in Fig. 33. The collecting bow is raised into contact with the trolley wire by springs and is lowered by air pressure, both movements being controlled by magnets and air valves. The storage-battery switch is closed, so that one of the two batteries is connected to the control circuit. To raise the collecting bow the plug shown in Fig. 32 is inserted in the reset receptacle on controller No. *1*, Fig. 33, thus joining contacts *B*+ and *6*. Starting from the positive battery terminal *B*+, the current path is as follows: *B*+ –knife switch–*B*+ –terminal *B*+ in junction box *2*–*B*+ in junction box *1*–*B*+ in reset receptacle of controller No. *1*–wire *6*–terminal *6* in junction box *1*–*6* in junction box *2*–wire *6*–right-hand valve magnet under the pantograph trolley–wire *91* to interlock *A1* of switch *11* in switch group–wire *93* to interlock *A1* of switch *9*–negative battery wire *B*— to negative terminal of the battery. The right-hand trolley valve magnet is energized, admitting air to the trolley unlock cylinder; this releases the latch that holds the collecting bow in its lower position and allows powerful springs to raise the bow into its active position.

79. To lower the collecting bow, the controller plug, which has two metal portions insulated from each other, is inserted in the cut-out receptacle, thus connecting together the front cut-out receptacle contacts *B*+, *8A*, and *10A* on controller No. *1*, Fig. 33, and also the back cut-out receptacle contacts *3* and *3A*. The right-hand button, indicated near the base of the controller, is then pressed. The button temporarily raises the contact segments so that fingers *10A* and *0* are connected. Starting from the front cut-out receptacle contact *B*+ on the controller, the path is: *B*+ –plug–contact *10A*–finger *10A*–contact segment–finger *0*–wire *0*, through junction boxes *1* and *2* to the left-hand valve magnet under the pantograph trolley–wire *B*— to negative terminal of the battery. The valve magnet admits air to the control cylinders and forces the collecting bow to its lower position, where it is locked. All of the current collectors on the

train may be operated from any one of the master controllers through the interconnecting control wires on the cars.

80. Control Circuits, First Notch.—After the current collector has been raised into contact with the trolley wire by the insertion of the plug into the reset receptacle of the master controller, the plug is inserted into the cut-out receptacle. Since the button on the controller base is not pressed, the circuit of the valve magnet for lowering the collecting bow is open. One of the metal portions of the plug connects receptacle contacts *3* and *3A*, Fig. 33. In order to obtain forward movement of the car, the controller handle is moved toward the right. On the first forward notch, drum finger *B*+ is connected through one of the drum segments, all of which are electrically connected, to finger *1*. The path is: finger *B*+–finger *1*–wire *1*–terminals *1* in junction boxes *1* and *2*–wire *1* to reverser interlock–wire *R1*–reverser operating coil *R1*–wire *90* to interlock *AA1* of switch *12* of switch group–wire *92*–interlock *AA1* of switch *10*–wire *B*— to negative terminal of battery. The reverser is thrown to forward position, and reverser interlock fingers *1* and *R* are connected by the lower reverser interlock segment. Current from the battery finger *B*+ on the master controller now flows through wire *1* to the lower reverser interlock segment–wire *R* to switch group–wires *11* and *12* in parallel–switch operating coils *9*, *10*, *11*, and *12* in parallel. This operates main switches *9*, *10*, *11*, and *12* and moves their interlocks so that the fingers occupy the position marked *switch closed*. At the same time finger *B*+ on the master controller is connected to finger *3A* and current flows through finger *3A*–plug contact–wire *3*–terminals *3* in junction boxes *1* and *2*–wire *3* to switch group–interlock *K* of switch *5*–wire *3*–switch-operating coil *1*–wire *B*— to negative terminal of battery. Main switch *1* is closed and its interlock *V* is in the *switch-closed* position. The closing of main switch *1* connects tapping *1* of the autotransformer to end *1* of the right-hand preventive coil.

81. Since the interlocks under switches *1*, *9*, and *11* of the switch group, Fig. 33, are closed, current can flow from wire *R* under the interlock of switch *11* to interlock *A1*–wire *13*–



CAR-WIRING DIAGRAM FOR TWO MOTORS

FIG. 33

interlock *A1* of switch *9*–wire *14* to interlock *V* of switch *1*–wire *15*–switch-operating coil *2*–wire *B*— to negative terminal of battery. Main switch *2* is now closed, connecting autotransformer tapping *2* to end *2* of the left-hand preventive coil. Since the interlock under main switch *2* is now closed, current can flow from junction *14* under this interlock through interlock *U* of switch *2*–wire *17*–switch-operating coil *3*–wire *B*—. Main switch *3* is closed, connecting tapping *3* to end *3* of the right-hand preventive coil. Since interlock *U* under main switch *3* is now closed, current can flow from junction *14*, under this interlock, to wire *19*–switch-operating coil *4*–wire *B*—. Main switch *4* is closed, connecting tapping *4* to end *4* of the left-hand preventive coil. Main switches *1*, *2*, *3*, *4*, *9*, *10*, *11*, and *12* and their interlocks are closed on the first notch, as indicated in the table of sequence of switches.

82. Motor Circuit, First Notch. — The circuit through the motors when the master controller is on the first forward notch is as follows: Main switches *1*, *2*, *3*, and *4*, Fig. 33, are connected to tappings *1*, *2*, *3*, and *4* on the autotransformer.

The path is from

tappings *1* and *3* – right-hand preventive coil – right half of middle preventive coil –

tappings *2* and *4* – left-hand preventive coil – left half of middle preventive coil –

wire *C*

switches *9* and *10* – wire *X* – reverser segment *X* to *A1*– – terminal *F1* – of motor-field winding – terminal *F1* + – finger *A1* + on reverser – finger *F1* + – terminal *A1* + on motor – motor armature – *A1* –

switches *11* and *12* – wire *Y* – reverser segment *Y* to *A2* + – terminal *F2* + of motor-field winding – terminal *F2*— – finger *A2* on reverser – finger *F2* + – terminal *A2* + on motor – motor armature – *A2* –

ground wire to earth.

The only change in the motor circuit for the succeeding notches of the master controller is in the connections to different

tappings of the autotransformer. The schematic diagram shows the essential motor circuits in simplified form. The shunts across the field coils of the motors are not always used. The effect of the shunts is to reduce the voltage drop across the fields and change the phase relation between the current in the armature and field to a greater or less extent.

83. Second Notch.—On the second notch, finger *3A*, Fig. 33, drops contact, and finger *4* makes contact with the drum of the master controller. Opening the circuit of the finger *3A* opens main switch *1*, thus disconnecting tapping *1* on the autotransformer and moving interlock *V* to the *switch-open* position. From drum finger *4*, current flows through wire *4* to the switch group–interlock *A1* of switch *6*–wire *16*–interlock *U*–wire *15*–switch-operating coil *2*–wire *B*— to negative terminal of battery. Switch *2* is thus held closed, although its control path through interlock *V* is broken. From junction *14*, under interlock *V*, current can now flow through interlock *V* to wire *21*–interlock *U* (closed)–wire *22*–switch-operating coil *5*–*B*—. Main switch *5* and its interlock are closed, and tapping *5* is connected to end *5* of the right-hand preventive coil. Switches *2*, *3*, *4*, *5*, *9*, *10* *11*, and *12* are closed on the second notch.

84. Third Notch.—On the third notch, finger *4*, Fig. 33, drops contact, and finger *5* makes contact with the drum of the master controller. The circuit through wire *4* is broken, thus allowing main switch *2* and its interlock *U* to open. Current from drum finger *5* now flows through interlock *A1* of switch *7*–wire *18*–interlock *U* of switch *3* (closed)–wire *17*–operating coil *3*–wire *B*—. Switch *3* is thus held closed, although its control path through interlock *U* of switch *2* is open. Current from junction *14*, under interlock *U* of switch *2* can flow through interlock *U*–wire *23*–interlock *K* (closed)–wire *24*–operating coil *6*–wire *B*—. Main switch *6* and its interlock are closed. Tapping *6* is connected to end *6* of the left-hand preventive coil. Switches *3*, *4*, *5*, *6*, *9*, *10*, *11*, and *12* are closed on the third notch.

85. Fourth Notch.—On the fourth notch, finger *5*, Fig. 33, drops contact and finger *6* makes contact with the drum of the master controller. The circuit through wire *5* is broken, thus allowing main switch *3* and its interlock *U* to open. From drum finger *6*, current now flows through interlock *A A1* of switch *8*–wire *20*–interlock *U* (closed)–wire *19*–switch-operating coil *4*–wire *B*—. Switch *4* is held closed, although its control path through interlock *U* of switch *3* is open. Current from junction *14* can now flow through interlock *U* of switch *3*–wire *25*–interlock *A1* of switch *6* (closed)–wire *26*–switch-operating coil *7*–*B*—. Main switch *7* and its interlock are closed. Tapping *7* is connected to end *7* of the right-hand preventive coil. Switches *4*, *5*, *6*, *7*, *9*, *10*, *11*, and *12* are closed on the fourth notch.

86. Fifth Notch.—On the fifth notch, finger *6*, Fig. 33, drops contact, and finger *7* makes contact with the controller drum. Control circuit through wire *6* is broken, thus allowing main switch *4* and its interlock to open. Current cannot flow from drum finger *7*, since controller terminal *7* is not connected to any car wire. Interlock *U* of switch *4* is open, so that current can flow from junction *14* under interlock *V* of switch *1*–wire *21*–interlock *U*–wire *27*–interlock *A1* of switch *7* (closed)–wire *28*–switch-operating coil *8*–*B*—. Main switch *8* and its interlock are closed. Tapping *8* is connected to end *8* of the left-hand preventive coil. Switches *5*, *6*, *7*, *8*, *9*, *10*, *11*, and *12* are closed on the fifth notch.

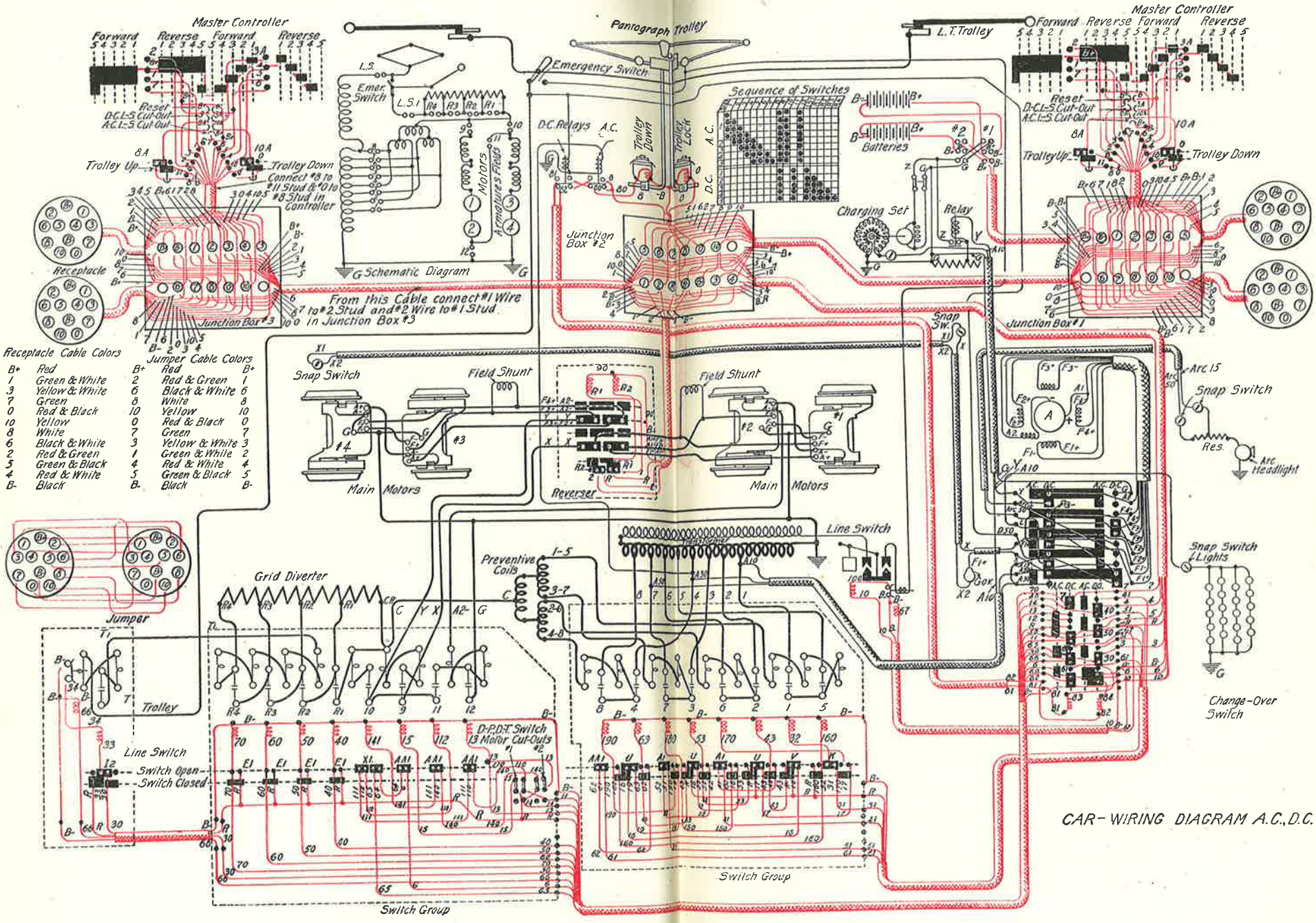
87. First Reverse Notch.—To reverse the direction of movement of the car the controller handle is moved to left. On the first reverse notch, Fig. 33, drum fingers *B*+ and *2* are active. Current flows from drum finger *2*–wire *2*–junction boxes *1* and *2*–wire *2*–reverser interlock segment–wire *R2*, now connected to *2*, as the reverser control segments are assumed to be at forward position–operating coil *R2*–wire *90* to switch group–wire *90*–*90*–interlock *A A1* of switch *12*–wire *92*–interlock *A A1* of switch *10*–wire *B*—. The reverser operating coil *R2* forces the reverser contact segments to reverse position. Reverser interlock finger *R2* drops contact with the interlock segment, thus breaking connection between it and finger *2*. At the same time, finger *R* makes contact with the same segment. Current flows

from reverser finger *2* to finger *R*–wire *R* to switch group–wire *R*–switch-operating coils *9*, *10*, *11*, and *12*, in parallel, thus operating the main switches *9*, *10*, *11*, and *12*. The action of the other control magnets and main switches is the same on the reverse notches as on the forward notches. The main field-coil connections of the motors are reversed, therefore the rotation of the motors is reversed.

WESTINGHOUSE ALTERNATING-CURRENT AND DIRECT-CURRENT UNIT SWITCH CONTROL

88. Apparatus for Direct and Alternating Current.—A diagram of the wiring of a car fitted with four motors and adapted to operate with either direct or alternating current is shown in Fig. 34. For direct-current working the motors are controlled by resistances, and for alternating current by an autotransformer. The requisite changes in connections are made by a change-over switch operated by a relay. Two types of current collectors are used: one of the pantograph type for use on high-tension alternating-current circuits, and the other of the ordinary wheel type similar to that used on tramcars for use on direct-current circuits.

89. Arrangement for Direct Current.—When the equipment is to be used on a direct-current circuit, one of the arms carrying a trolley wheel is raised so that contact is made with the trolley wire. Current then flows from the current collector through the coil of the direct-current relay and to earth at *G*, Fig. 34. The plunger of the relay is drawn up, thus making connection between the upper contacts *81*. The change-over switch is placed in the proper position for direct-current operation as follows: The plug of the left-hand master controller is placed in the alternating-current line-switch cut-out receptacle so that contact *B*+ is connected to contact *8A*, and current flows to contact *8A*–stud *11*–wire *8*–contact points *80* on *A. C.* relay (lower position)–contacts *81* on *D. C.* relay, as relay is now active–wire *81* to operating coil of change-over switch–wire *83*–change-over switch interlock segment, if switch has been left at *A. C.* position–wire *B*— to negative terminal of battery. The switch is pulled to the direct-current position shown in the diagram.



Receptacle Cable Colors

B+	Red
1	Green & White
3	Yellow & White
7	Green
0	Red & Black
10	Yellow
8	White
6	Black & White
2	Red & Green
5	Green & Black
4	Red & White
B-	Black

Jumper Cable Colors

B+	Red
2	Red & Green
6	Black & White
8	White
10	Yellow
0	Red & Black
7	Green
3	Yellow & White
1	Green & White
4	Red & White
5	Green & Black
B-	Black

CAR-WIRING DIAGRAM A.C., D.C.

Fig. 34

90. Operation on Direct Current. — After the change-over switch has been set for direct current, the plug of the master controller is placed in the direct-current line-switch cut-out receptacle. When the controller handle is moved to the first notch, finger *3A*, Fig. 34, is active, and current flows through the plug to contact *3*–wire *3* to finger *30* on the change-over switch–wire *30*–interlock of *D. C.* line switch–wire *33*–line-switch operating coil–wire *34*–wire *B*—. The line switch is thus closed. Finger *1* on the master controller is used for forward running, and when this finger is active, the reverser operating coil *R1* is energized and the reverser is thrown to forward position. Wire *R* at the reverser interlock is now active, and, as the operating coil of switch *9* takes current from this wire through wire *15*, switch *9* closes. Finger *11* on the change-over switch is energized from finger *R*, and current flows through wire *11* to the switch group–wire *110*–interlock *A A1* of switch *12*–wire *111*–wire *112*–operating coil of switch *11*. Switch *11* closes. The four motors are in series, with all the resistance sections in circuit. Further movement of the controller energizes fingers *4*, *5*, *6*, and *7* and cuts out the four resistance sections. The four motors are now in series, with all the resistance sections cut out.

91. Arrangement for Alternating Current. — If alternating current is to be used, the plug of the master controller is inserted in the alternating-current line-switch cut-out receptacle, Fig. 34. The alternating-current line switch is closed by current that flows from the plug contact *B*+ through cut-out contact *10A* – finger *10* – wire *10* – operating coil of the *A. C.* line switch – wire *100* – wire *B*— to negative terminal of battery. The pantograph current collector is raised by pressing the left-hand button at the base of the controller. Stud *8* and wire *0* are now active, and current flows through the operating coil of the trolley lock. The latch on the pantograph collector is released, and the collecting bow is forced upwards by springs.

92. As soon as the collecting bow touches the trolley wire, current flows through the coil of the alternating-current relay from autotransformer tapping *4*, Fig. 34. The plunger of the relay is raised so that contact is broken between the lower

points *80*. Therefore, when the left-hand button on the base of the controller is released and finger *8A* is connected to stud *11* and wire *8*, no current can flow between the lower relay contacts *80* and through the trolley-down magnet. The change-over switch is forced to its alternating-current position by current flowing from the positive battery terminal to the contact *B*+ of the controller plug–stud *11*–wire *8*–upper contact *8* on the alternating-current relay across the disc to contacts *82* of *D. C.* relay–wire *82*–operating coil of change-over switch–wire *84*–wire *B*— to negative terminal of battery. If the switch is in direct-current position, it is pulled into alternating-current position.

93. Operation on First Notch.—On the **first notch** of the master controller, either finger *1* or finger *2*, Fig. 34, is active, depending on whether the controller is thrown to forward or to reverse position. In either case wire *R* at the reverser interlock is energized, and this energizes wires *14* and *13* at the interlocks of the change-over switch, which is in the alternating-current position. Switches *9*, *10*, and *12* are thus closed. Switch *1* is closed by current through master-controller finger *B*+ –finger *3A*–wire *3*–segment of change-over switch–wire *31*–wire *32*–operating coil of switch *1*. Switch *2* is closed by current from wire *R* through the closed interlock of switch *1* and wire *43*. Switch *3* is closed by the current passing through the closed interlock of switch *2* and wire *53*. Switch *4* is closed by the current passing through the closed interlock of switch *3* and wire *63*.

94. Operation on Second and Third Notches.—On the **second notch,** finger *3A*, Fig. 34, drops contact and switch *1* opens. When wire *4* becomes active, wire *41* is energized at the change-over switch and switch *2* is held closed. The current can now flow through the wire *R*–interlock of switch *1* (open)–wire *16*–interlock of switch *4* (closed)–wire *160*–operating coil of switch *5*. Switch *5* closes.

On the **third notch,** finger *4* drops contact, and finger *5* is energized. Switch *2* opens, since wire *41* is dead, and circuit *R*, through its operating coil, was broken when switch *1* opened. Current from wire *R* flows through the interlock of switch *2* (open)–wire *17*–interlock of switch *5* (closed)–operating coil of switch *6*. Switch *6* closes. Circuit *R*, through the operating coil of switch *3*, is broken by the interlock of switch *2* (now open), but current flows through operating coil *3* from wire *51*.

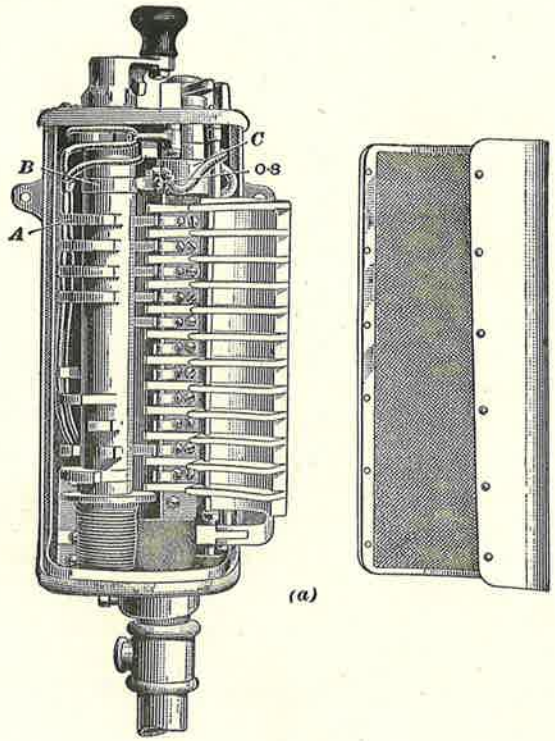
95. Operation on Fourth and Fifth Notches.—On the **fourth notch,** wires *5* and *51*, Fig. 34, are dead, and wire *61* is active. Switch *3* opens because wire *51* is dead. Current from the wire *R* flows through the interlock of switch *3* (open)–wire *18*–wire *180*–operating coil of switch *7*. Switch *7* closes. Circuit *R*, through the operating coil of switch *4*, is now broken, but the coil obtains current from wire *61*.

On the **fifth notch,** wires *6* and *61* are dead, and switch *4* opens. Wire *7* is dead when the change-over switch is at its alternating-current position. Current from circuit *R* can now flow through the interlock of switch *1*–wire *16*–wire *19*–wire *190*–operating coil of switch *8*. Switch *8* closes. The maximum E.M.F. is now impressed on the motors.

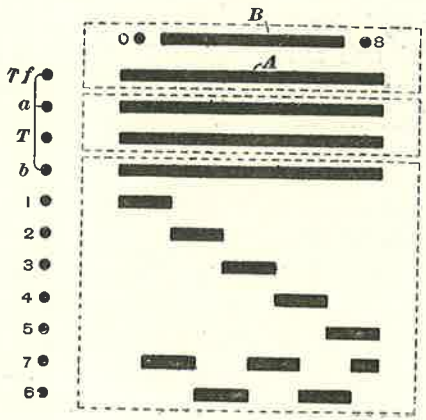
96. Method of Lowering Pantograph Collector.—If the current collector is to be lowered, the right-hand button of the master controller is pressed, thus breaking the circuit of wire *10* and causing the alternating-current line switch to open. The alternating-current relay contact plate drops and completes wire circuit *8* through the trolley-down magnet. Air under pressure is forced into the main cylinder of the pantograph, and the collecting bow is lowered and automatically latched. If the collecting bow is to remain down, the plug may be drawn out of the alternating-current line-switch cut-out.

SPRAGUE GENERAL ELECTRIC ALTERNATING-CURRENT MULTIPLE-UNIT SYSTEM

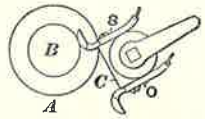
97. In the Sprague General Electric alternating-current multiple-unit system the contactors are operated by alternating-current electromagnets, which are supplied with current at low tension from the autotransformer and controlled from a master controller, which is shown in Fig. 35 (*a*). The segments opposite the eight lower fingers *b* to *6*, view (*b*), constitute the



(a)



(b)



(c)

FIG. 35

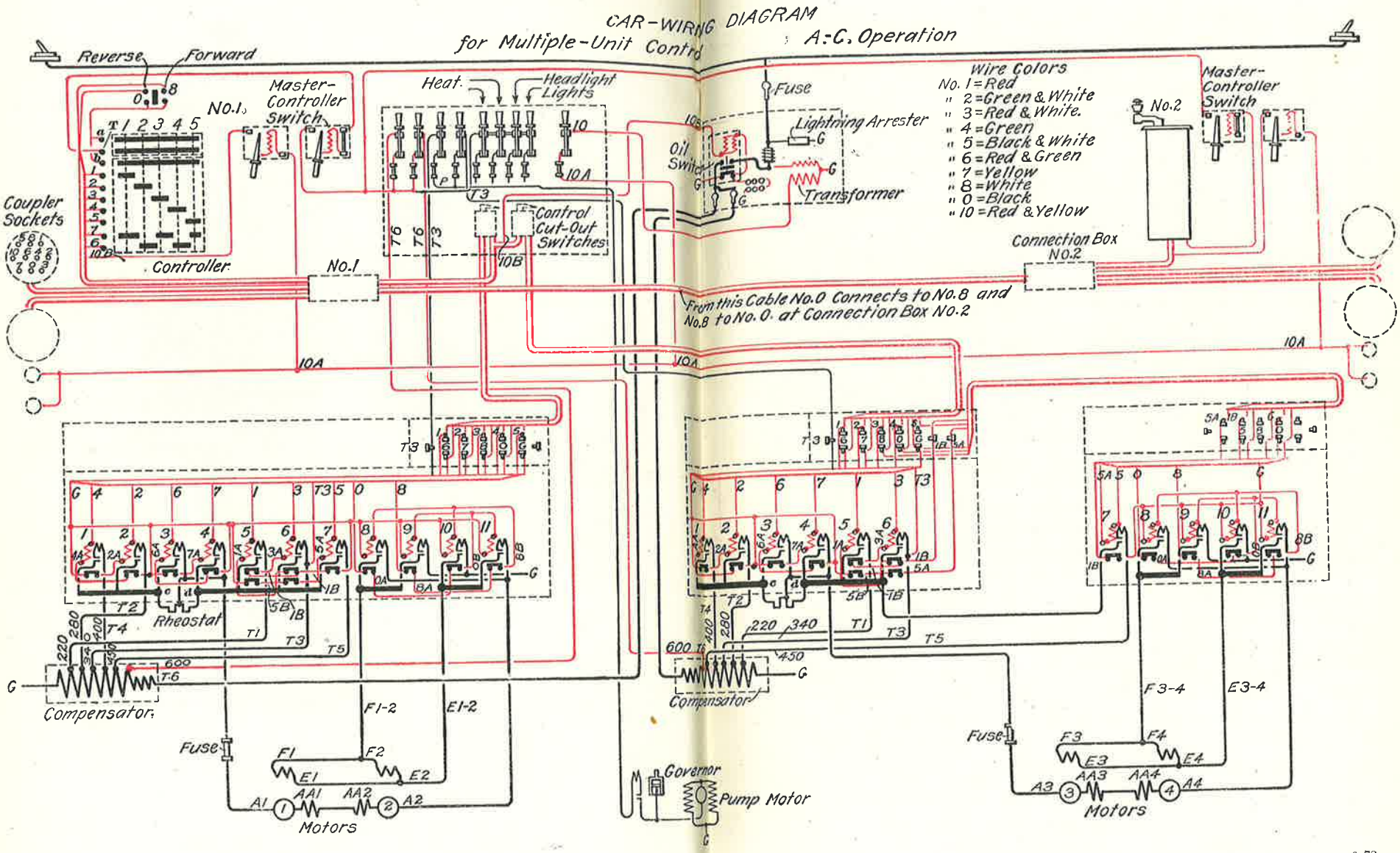

CAR-WIRING DIAGRAM
for Multiple-Unit Contrd
A.C. Operation
Reverse
Forward
Master-Controller Switch
No.1
Heat
Headlight Lights
Fuse
Lightning Arrester
Oil Switch
Transformer
Wire Colors
No. 1 = Red
" 2 = Green & White
" 3 = Red & White.
" 4 = Green
" 5 = Black & White
" 6 = Red & Green
" 7 = Yellow
" 8 = White
" 0 = Black
" 10 = Red & Yellow
No.2
Master-Controller Switch
Coupler Sockets
Controller
Control Cut-Out Switches
Connection Box No.2
From this Cable No.0 Connects to No.8 and No.8 to No.0. at Connection Box No.2
Rheostat
Compensator
Fuse
Governor
Pump Motor
Motors
F1-2
E1-2
F3-4
E3-4

Fig. 36

accelerating section of the drum. The power section takes in the two segments opposite the fingers *T* and *a*. The reverse section consists of segment *A* opposite finger *r f*, and segment *B* opposite either finger *0* or *8*. Segments *A* and *B* are electrically connected and receive current through finger *r f*. The reverse fingers *0* and *8*, one directly behind the other, are mechanically connected to the reverse cylinder *C*, view (*a*). Either finger *0* or finger *8* may be connected to the drum segment *B* by throwing the reversing handle either to the forward or to the reverse position, as shown in view (*c*). For the forward position, finger *8* is active, and for reverse position, finger *0* is active. The coiled spring at the bottom of the case, view (*a*), serves to return the controller handle to off-position in case of emergency.

98. Car-Wiring Diagram. — A car-wiring diagram for the alternating-current operation of two master controllers connected to four motors is shown in Fig. 36. The system is duplex; that is, the control circuit, the compensator or autotransformer, and the contactors are distinct with each pair of motors. A small autotransformer, which is shown near the oil switch, provides current for the operating coil of the switch. One end of the secondary coil of this transformer is earthed near the transformer, and the other end is earthed through switch *10*–wire *10A*–left-hand master-controller switch–wire *10B*–connecting box No. *1*–wire *10B*–operating coil of oil switch–earth at *G*. When switch *10* is closed, the operating coil of the oil switch closes the oil switch, and currents flow through the two compensators to earth. When the oil switch closes, the interlock under it opens, and the operating coil is earthed through a resistance. Just sufficient current flows to allow the operating coil to retain the switch in its closed position and yet not cause heating of the coil.

99. Wires are numbered or lettered alike at points where they enter and leave the multicore cable. The action of controller No. *1*, Fig. 36, will be considered with the reverse cylinder, situated at the top of the controller, in the forward position; that is, with finger *8* in contact with its segment. The currents for the control circuits are obtained from tappings *T6* of the

two compensators through the two knife switches shown at the left of the group of switches. The wires of the control circuit are indicated by red lines, and the wires of the power circuit by black lines.

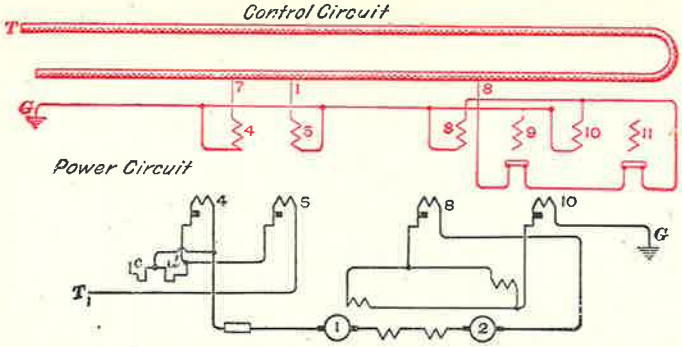
100. First Point.—On the first point, current flows from the master-controller switch to finger *T*, thence to the two drum segments, finger *a*, and to the lower right-hand finger of the reverse cylinder. Two lower reverse-cylinder fingers are shown in Fig. 36, but in the actual controller only one finger *r f*, Fig. 35 (*b*), is used. From the reverse cylinder, Fig. 36, the current path for the control of one set of motors is as follows: Finger *8*–connection box No. *1*–right-hand control cut-out switch–terminals *8*, *8*–interlock below contactor *9*–wire *8A*–interlock below contactor *11*–wire *8B*–operating coils of contactors *8* and *10* in parallel, and thence to the common earth wire *G*. From finger *a* on the master controller current also flows to finger *b*–finger *1*–connection box No. *1*–right-hand control cut-out switch–terminal *1*–wire *1*–operating coil of contactor *5*–terminal *1A*–upper interlock below contactor *6*–wire *1B*–terminals *1B*–wire *1B*–interlock below contactor *7*–common earth wire *G*.

From finger *7* on the master controller current flows through connecting box No. *1*–right-hand control cut-out switch–terminal *7*–wire *7*–operating coil of contactor *4*–terminal *7A*–interlock below contactor *3*–earth wire *G*. The main switches *4*, *5*, *8*, and *10* are closed by the action of their operating coils. Compensator tapping *T1* is connected to contactor *5*.

101. The two motor armatures, Fig. 36, are permanently connected in series, the compensating motor windings are connected directly in series with the armatures, and the fields of the two motors are connected in parallel. As the controller is operated, the same action is taking place in the one set of motors as in the other.

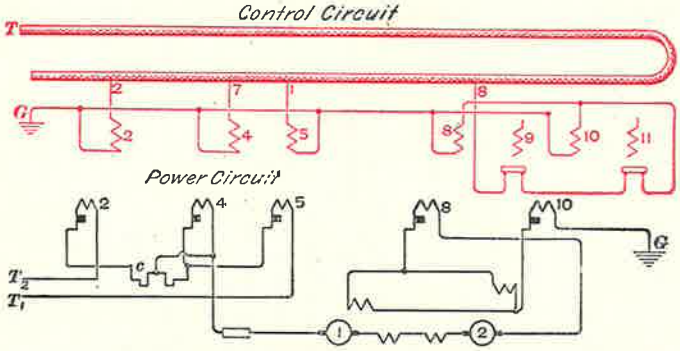
102. First Intermediate Position.—Soon after leaving the first point, Fig. 36, finger *1* drops contact, and at the same time finger 2 makes contact. When fingers *1*, *2*, and *7* are all active

1ST POINT
Control Circuit



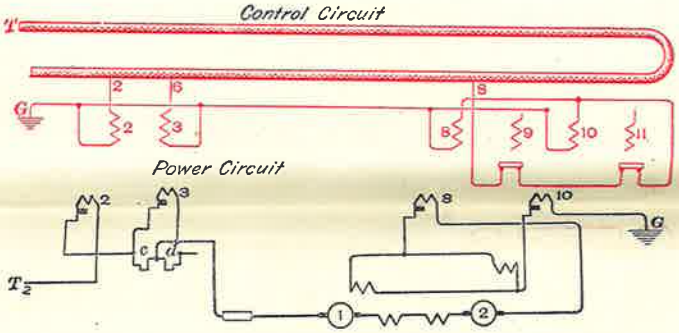
Power Circuit

1ST INTERMEDIATE POSITION
Control Circuit



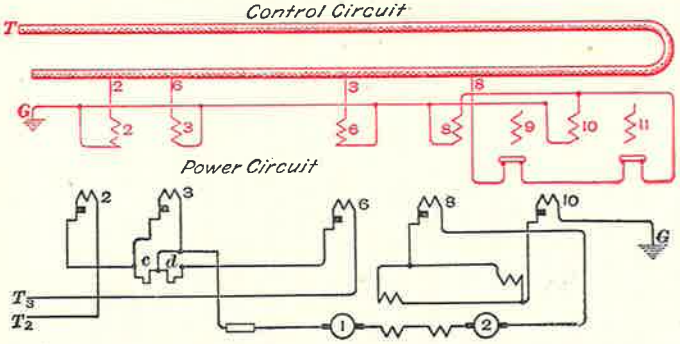
Power Circuit

2D POINT
Control Circuit



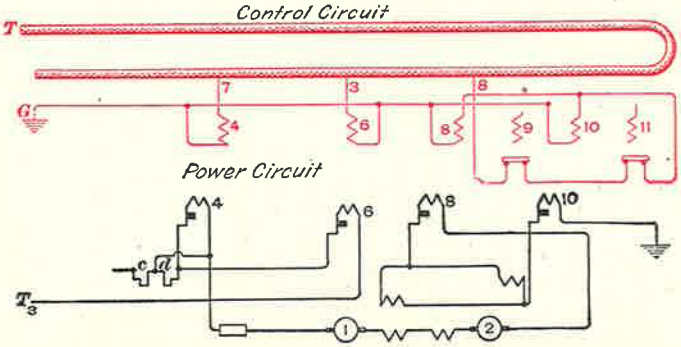
Power Circuit

2D INTERMEDIATE POSITION
Control Circuit



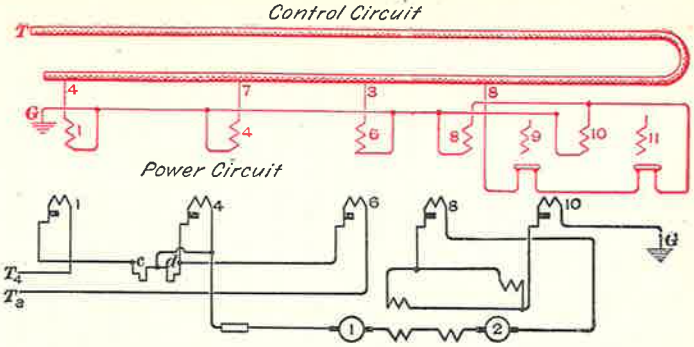
Power Circuit

3D POINT
Control Circuit



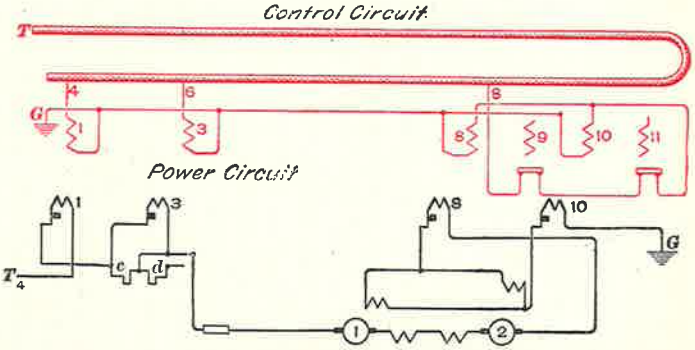
Power Circuit

3D INTERMEDIATE POSITION
Control Circuit



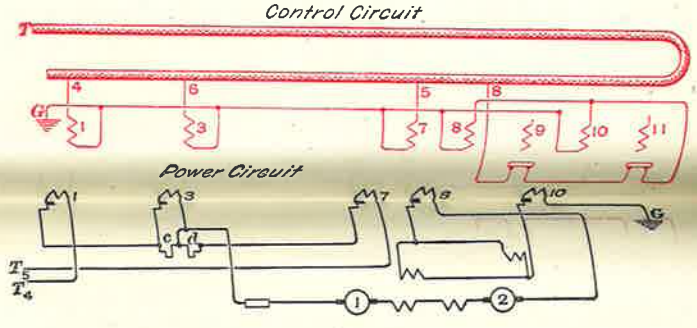
Power Circuit

4TH POINT
Control Circuit



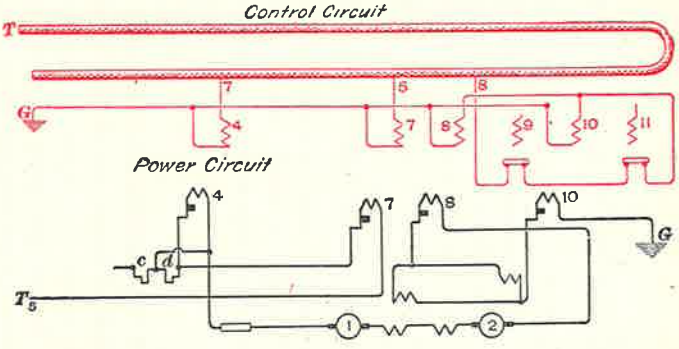
Power Circuit

4TH INTERMEDIATE POSITION
Control Circuit



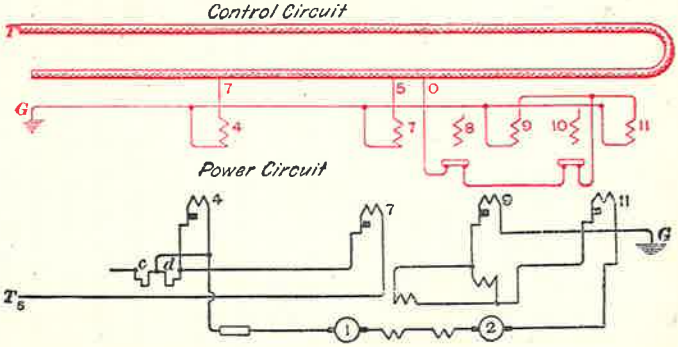
Power Circuit

5TH POINT
Control Circuit



Power Circuit

5TH POINT REVERSE SWITCH AT REVERSE POSITION
Control Circuit



Power Circuit

FIG. 37

§ 72

for an instant, contactors *5*, *2*, and *4* are closed. The motors are still connected to tapping *T1* by contactors *5* and *4*, but tappings *T1* and *T2* are bridged by section *c* of the rheostat. When finger *1* drops its contact, contactor *5* opens, thus cutting out tapping *T1* and allowing all the current to flow through the tapping *T2* – contactor *2* – section *c* of the rheostat – contactor *4* and wire from the centre of the rheostat, to the motors.

103. Second Point. — On the second point, finger *7* drops contact, and finger *6* makes contact with the drum segments. Contactor *4* opens and contactor *3* closes, thus cutting out section *c* of the rheostat. The motors are now connected directly to tapping *T2*.

104. Second Intermediate Position.—On the second intermediate position, finger *2* drops contact, and finger *3* makes contact. Contactor *2* opens, and contactor *6* closes. At the instant when both contactors *2* and *6* are closed, section *d* of the rheostat is bridged across tappings *T3* and *T2*. When contactor *2* opens, all the current flows from tapping *T3* through section *d* of the rheostat to the motors.

105. Third Point.—On the third point, finger *6* drops contact, and finger *7* makes contact. Contactor *3* opens and contactor *4* closes, thus short-circuiting resistance section *d* and leaving the motors connected directly to tapping *T3*.

106. Remaining Points. — The connections of the devices in the control circuits and the motor connections for the remaining points and intermediate positions are shown in Fig. 37. When moving through the intermediate positions, a rheostat section is shunted across two compensator tappings; then, the lower voltage tapping is dropped and the resistance section is left in circuit. Finally, this resistance is short-circuited, and the motors are left connected directly to the high-voltage tapping, when the controller movement to a full point is completed. On the **fifth point** the maximum voltage is impressed on the motors, as motor tapping *T5* is active.

107. Operation of Reverse Cylinder. — When the reverse cylinder on the master controller, Fig. 36, is thrown to the

reverse position, contactors *8* and *10* are opened, and the lower left-hand reverse-switch finger is connected to finger *0*–connecting box No. *1*–right-hand control cut-out switch–terminal *O*–wire *0*–interlock below contactor *8*–terminal *O A*–interlock below contactor *10*–wire *O B*–operating coils of contactors *9* and *11* in parallel–earth wire *G*. Contactors *9* and *11* are closed. The connections of the armatures remain unchanged, but the field connections have been reversed, as is shown by the fifth reverse point, Fig. 37. The direction of rotation of the motors is therefore reversed.

MULTIPLE-UNIT CONTROL OF COMPENSATED REPULSION MOTORS

108. The multiple-unit system of control is applied by the Allgemeine Elektricitats Gesellschaft to the control of the Winter-Eichberg compensated repulsion motor. Railways operating successfully with these motors have been constructed on the Continent, and a portion of the London, Brighton, and South Coast Railway has recently been equipped with them. The master controllers used for this system are similar to those used on other multiple-unit systems, and only have to handle the small currents required to operate the contactors. The method of speed control adopted is very similar to that previously described.

109. Car-Wiring Diagram.—The diagram of connections for a motor coach used on the London, Brighton, and South Coast Railway is shown in Fig. 38, the operating circuits being shown in red and the main power or motor circuits in black. Each coach is fitted with four 150-horsepower motors, and the connections are so arranged that the motors can be worked through step-down transformers from a trolley wire at a pressure of 6,600 volts. The motors on the coach are operated in pairs, each motor having a separate exciter autotransformer, and each pair of motors being provided with a separate main transformer and with separate contactors. The current for operating the contactors, lighting, and heating is furnished at a pressure of 300 volts by the secondary of a small auxiliary step-down transformer, the

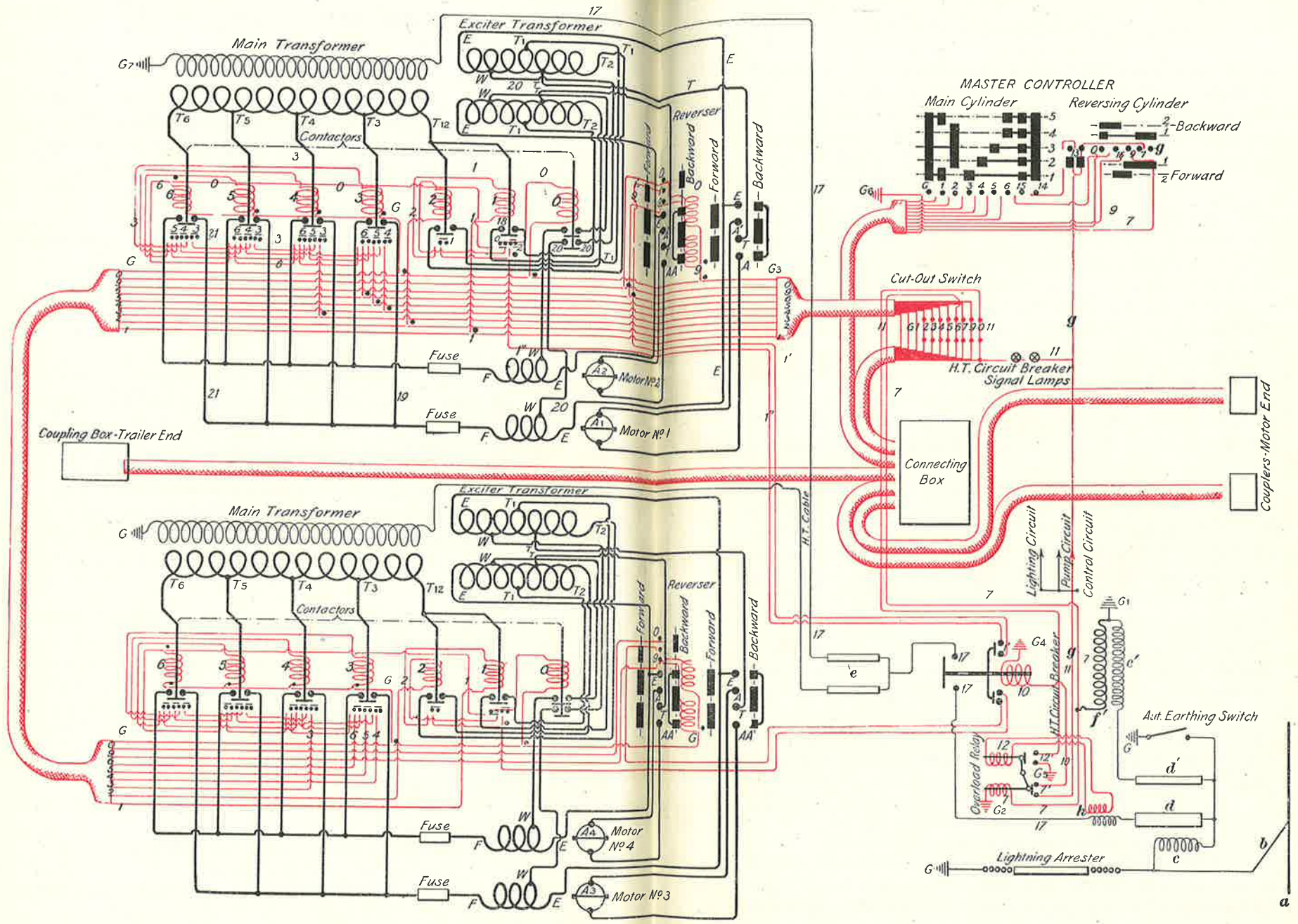

Main Transformer
Exciter Transformer
Contactors
Reverser
Forward
Backward
MASTER CONTROLLER
Main Cylinder
Reversing Cylinder
Cut-Out Switch
H.T. Circuit Breaker
Signal Lamps
Connecting Box
Coupling Box-Trailer End
Couplers-Motor End
H.T. Cable
Fuse
Motor No 1
Motor No 2
Motor No 3
Motor No 4
Lighting Circuit
Pump Circuit
Control Circuit
H.T. Circuit Breaker
Overload Relay
Aut. Earthing Switch
Lightning Arrester

Fig. 38

§ 72

primary of which is connected to the 6,600-volt circuit as soon as the collector bow is placed in contact with the trolley wire. All the contactors are fitted with interlock contacts, so that the contactors can only close in the proper order. The master controller has both main and reversing cylinders operated by separate handles.

110. Operation of Main Circuit-Breaker and Reverser.—Preparatory to starting the coach, the collector bow is raised into contact with the trolley wire. Current then flows in the control circuit, Fig. 38, from the trolley wire *a* – collector *b* – choking coil *c* – high-tension fuse *d'* – primary *e'* of auxiliary transformer to earth at *G1*. The auxiliary transformer is thus energized, and the secondary *f'* is ready to supply current for the operating circuits. To start the coach in a forward direction, the reversing cylinder of the master controller is placed in forward position *1*. Operating current then flows as follows: Secondary *f'*–wire *g*–contact finger *g* on reversing cylinder–contact segment on reversing cylinder–

contact finger *7* – wire *7* – connecting box – blade *7* of cut-out switch – wire *7* – operating coil *7* of overload relay – earth at *G2*.

contact finger *9* – wire *9* – connecting box – blade *9* of cut-out switch – wire *9* – contact finger *9* of reverser – operating coil *9*–earth wire *G3*.

The energizing of operating coil *7* of the overload relay causes it to close the contacts *7'*, which are held closed mechanically. Coil *10* of the high-tension circuit-breaker is energized through the following circuit: Secondary *f'*–wire *g*–contacts *7'*–wire *10*–operating coil *10* – earth at *G4*. The high-tension automatic circuit-breaker then closes. Owing to operating coil *9* on the reverser being energized, the reverser is pulled to the forward position, so that the segments marked *forward* make connection with the contact fingers.

111. The reversing cylinder on the master controller, Fig. 38, is then moved to forward position *2*; this disconnects contact finger *7*, and therefore operating coil *7* on the overload relay is de-energized, leaving the overload relay free to be operated by

coil *12*, which is connected to the secondary of the current transformer *h*. When the main high-tension current passing through the primary of current transformer *h* reaches too great a value, coil *12* operates the overload relay, which opens contacts *7'*, and thus de-energizes operating coil *10* of the high-tension circuit-breaker. The circuit-breaker is then opened by the action of a spring. A circuit is also provided through the high-tension automatic-switch signal lamps as follows: Secondary *f'*–wire *g*–wire *11*–signal lamps–blade *11* of cut-out switch–wire *11*–contacts *12'* on overload relay–earth at *G5*. The signal lamps then light, indicating that the circuit-breaker has opened.

In the second forward position of the reversing cylinder of the master controller the supply to operating coil *9* on the reverser is continued, when the main cylinder of the master controller is in one of the working positions; the path is from wire *g*, through contacts *13* and contact fingers *14*, *15*, and *16*, on the master controller, to wire *9*. The reverser is thus held in the forward position.

112. Operating Circuits, First Position of Controller.—When the main cylinder of the master controller, Fig. 38, is moved to the first position, the operating current for one reverser and group of contactors flows as follows: Secondary *f'* of auxiliary transformer–wire *g*–contacts *13*–contact finger *14*–contact segments on main cylinder of master controller–contact finger *3*–connecting box–blade *3* of cut-out switch–wire *3*–interlock *3* of contactor *4*–interlock *3* of contactor *5*–interlock *3* of contactor *6*–wire *3*–operating coil of contactor *3*–earth wire *G 3*. Contactor *3* closes.

Owing to the reverser being in the forward position, operating current flows from contact finger *9* on reverser – contact segment–contact finger *1'* on reverser–wire *1'*–auxiliary contacts *1'* on high-tension circuit-breaker – wire *1''* – interlock *1* of contactor *2*–wire *1*–operating coil of contactor *1*–wire *1*–blade *1* of cut-out switch–connecting box–contact finger *1* on main cylinder of master controller – segments of master controller – contact finger *G*–earth at *G 6*. Contactor *1* then closes. Thus, in the first position of the master controller, contactors *1* and *3* are closed.

113. Power Circuits, First Position. — The main power or motor circuit for one half of the equipment in Fig. 38, consisting of main transformer, exciter autotransformers, and pair of motors, is then as follows, the circuit for the other half of the equipment being exactly similar: Overhead line *a* – collector bow *b* – choking coil *c* – fuse *d* – primary of current transformer *h* – wire *17* – contacts *17* on high-tension circuit-breaker – isolating switch *e* – wire *17* – primary of main transformer – earth at *G7*. The main transformer is thus energized. Contactors *1* and *3* are closed so that the secondary circuits through motor No. *1*

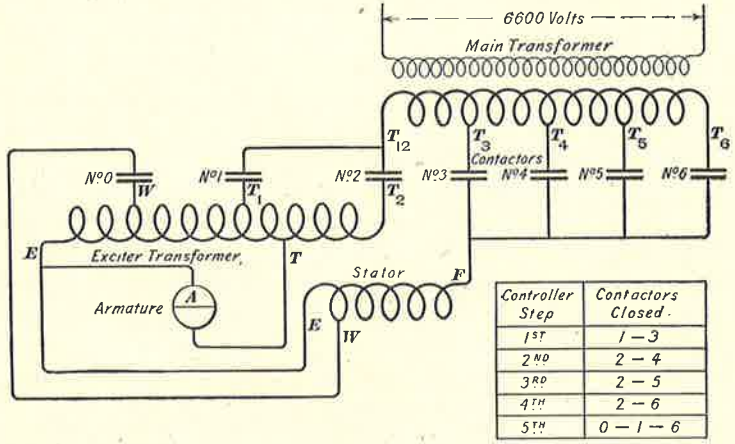


FIG. 39

are as follows: Tapping *T12* on secondary of the main transformer – contact *18* of contactor *1* – wire *T1* – tapping *T1* of exciter autotransformer – winding of autotransformer from *T1* to *E* – wire *E* – field *E F* of motor No. *1* – fuse – wire *19* – contact of contactor *3* – tapping *T3* on main transformer. This circuit does not include the armature of the motor, the circuit through the armature being from wire *E* – finger *E* on reverser – reverser segment – finger *A'* – armature *A1* – finger *A* – finger *T* – wire *T* – tapping *T* on exciter autotransformer. The auxiliary winding *E W* of the stator of the motor is in series with the main winding for all positions of the controller except the final running position.

The power circuit outlined in the preceding paragraph may be more easily traced by reference to Fig. 39, which shows only the connections for the power circuit for a single motor. Corresponding parts and tappings are lettered the same in both Fig. 38 and Fig. 39. In Fig. 39 is given a list of the controller steps or positions and the contactors which are closed for each step.

114. Second, Third, and Fourth Positions of Controller.—In the second position of the controller the earth connection to the operating coil of contactor *1*, Fig. 38, is broken, so that contactor *1* opens, and in doing so closes interlock *2* beneath it. Contactor *2* closes, its earth connection being completed through interlock *2* and contact finger *2* on the master controller. The operating coil of contactor *3* is de-energized because finger *3* on the master controller breaks contact with the segment, and as finger *4* makes contact, contactor *4* is energized; hence contactor *3* opens and *4* closes. Thus, contactors *2* and *4* are closed in the second controller position, and the power circuits can be followed by reference to Fig. 39. If the circuits are traced out in Fig. 38 for the third and fourth controller positions, it will be found that in the third position contactors *2* and *5* are closed, and in the fourth position contactors *2* and *6* are closed. The effect of the various changes of connections is to cut successively into circuit the sections *T12–T3*, *T12–T4*, *T12–T5*, and *T12–T6* of the main transformer, thus increasing the E.M.F. applied to the motor terminals and causing the speed to increase. These changes may be followed by referring to the simplified diagram.

115. Fifth Controller Position.—In the fifth and final running position, the operating coils of contactors *1* and *6*, Fig. 38, are energized through circuits completed on the main cylinder of the master controller. When contactor *1* closes, the interlock *0* underneath it is also closed. This provides a path for operating current to pass from wire *6* (near contactor *6*) to wire *0*, through interlock *0* beneath contactor *1*, to wire *0* and thence to operating coil of contactor *0*, which closes. Thus, contactors *0*, *1*, and *6* are closed, so that the maximum E.M.F.'s due to both the main and exciter transformers are impressed on the motor.

The main secondary circuit for motor No. *1* is then as follows: Tapping *T12* on main transformer–contact *18*–wire *T1*–tapping *T1* on exciter autotransformer–winding from *T1* to *E*–wire *E*–field winding *EF* of motor No. *1*–fuse–wire *21*–contact of contactor *6*–terminal *T6* of main transformer. The armature of motor No. *1* is connected from terminal *E*–finger *E* on reverser–finger *A'*–armature *A1*–finger *A*–finger *T*–wire *T*–tapping *T* on exciter autotransformer. The auxiliary stator winding *E W* of the motor is connected by means of wire *20*–contacts *20* of contactor *0*–wire *20* to tapping *W* on the exciter autotransformer. The E.M.F. impressed on the auxiliary winding *E W* by the transformer windings between *W* and *E* sends a current through the auxiliary stator coils of the motor and aids in securing sparkless commutation at high speed. The main high-tension circuit is provided with a lightning arrester, and with an automatic earthing switch, by which the whole of the high-tension apparatus on the motor coach is connected to earth when it is necessary to execute repairs.

CURRENT COLLECTORS

PANTOGRAPH TROLLEY

116. Construction of Pantograph Trolley.—In single-phase railway work, as in three-phase work, current is nearly always collected from the overhead conductor by means of some form of bow collector. A Westinghouse **pantograph trolley** is shown in its raised position in Fig. 40 (*a*). The trolley is secured to the top of the locomotive or coach by the feet *a*, which are insulated from the other parts of the frame by the massive insulators *b*. The main operating cylinder *c* contains pistons which are connected by means of crossheads to levers *g* and *h*. A trolley lock or latch cylinder *d* is placed above the main cylinder. A hook *e* on the lower side of contact shoe *f* engages with the latch when the trolley is in its lowered position, as in view (*b*). The main contact shoe consists of a strip of galvanized iron, which is usually made about 6 inches wide, so as to have a large surface in contact with the wire. The upper surface of the shoe is furnished with

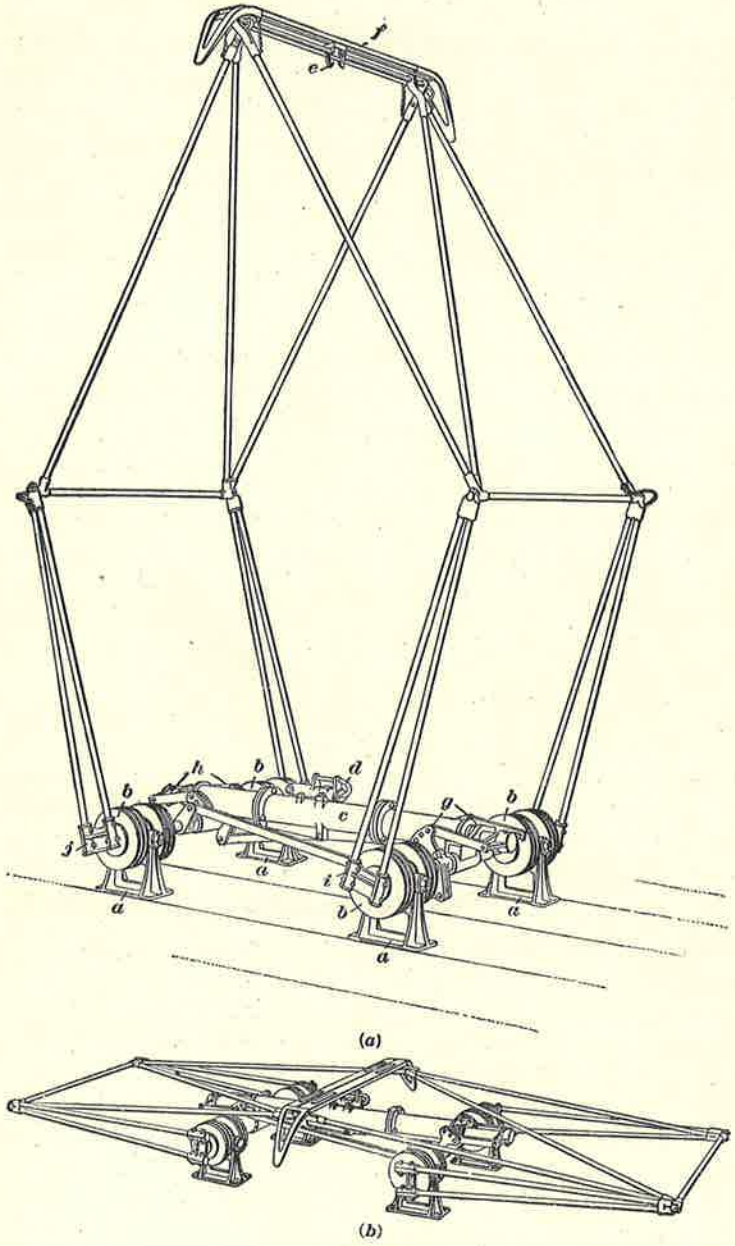


FIG. 40

grooves in which grease is placed; this acts as a lubricant, and reduces the friction between the shoe and the wire. It is customary to zigzag, or stagger, the trolley wire slightly, so that the wear on the conducting surface of the shoe will be distributed. The shoe is so long that it is impossible for it to leave the wire under normal conditions.

117. Operation of Pantograph Trolley.—The pantograph is worked by means of compressed air, supplied through pipes connected to the main cylinder and to the latch cylinder. The pantograph is normally held in a raised position against the wire by compression springs *k*, Fig. 41 (*a*). These springs force

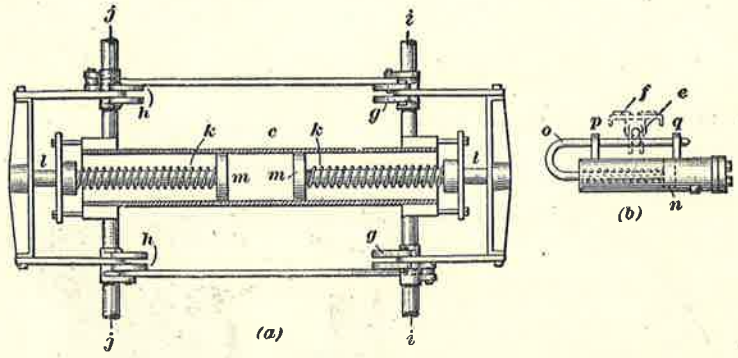


FIG. 41

piston rods *l* and pistons *m* toward the centre of the main cylinder *c*, thus causing short levers *g* and shaft *i*, Figs. 40 (*a*) and 41 (*a*), to rotate in a counter-clockwise direction, and levers *h* and shaft *j* to rotate in a clockwise direction. The arms attached to the shafts are forced upwards, and the shoe is pressed against the conductor wire.

118. In order to lower the collecting bow, compressed air is allowed to flow into the centre of the main cylinder. The pistons *m*, Fig. 41 (*a*), are forced outwards, shaft *i* is rotated in a clockwise direction, shaft *j* is rotated in a counter-clockwise direction, and the trolley is lowered to the position shown in Fig. 40 (*b*). When in this position, the hook *e*, Fig. 40 (*a*), which is divided into two parts, automatically catches round a projection

from latch-cylinder piston *n*, Fig. 41 (*b*), which forms latch *o*, now in its closed position. A spring in the latch cylinder normally keeps piston *n* in such a position that the latch *o* extends through lugs *p* and *q* on the cylinder, and when the trolley is down, through hook *e* on the contact shoe *f*. The compressed air is then turned off from the main cylinder, and the latch holds the collecting bow down. When it is desired to raise the trolley, air is momentarily admitted into the latch cylinder, which moves piston *n* and latch *o* so as to release hook *e*. The main cylinder springs then raise the trolley. The air in the main cylinder between pistons *m*, Fig. 41 (*a*), acts as a buffer as the pistons are forced toward each other, thus preventing too sudden action of the springs.

OERLIKON COLLECTOR

119. Construction of Collector.—The type of collector adopted by the Oerlikon Company of Zurich is shown in Fig. 42. This

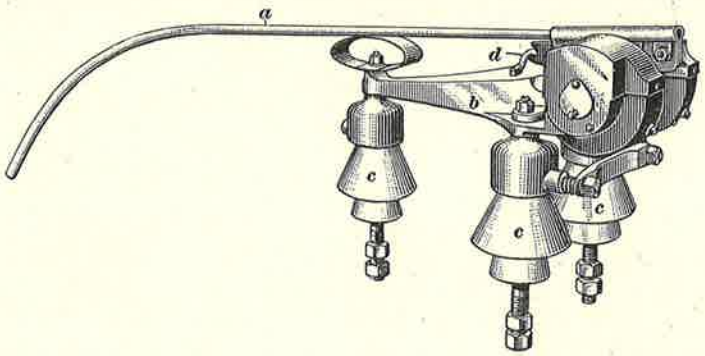


FIG. 42

type of collector differs considerably from collectors of the bow and pantograph varieties in that it will collect current from the side, upper, or lower surfaces of the conductor wire as may be required. The contact surface is a replaceable brass strip fitted to a curved steel tube *a*, which can rotate about an axis at one end through 180°. It is pressed against the conductor wire by a helical spring, which is not shown. The framework *b* of the collector is supported on the porcelain insulators *c*, which

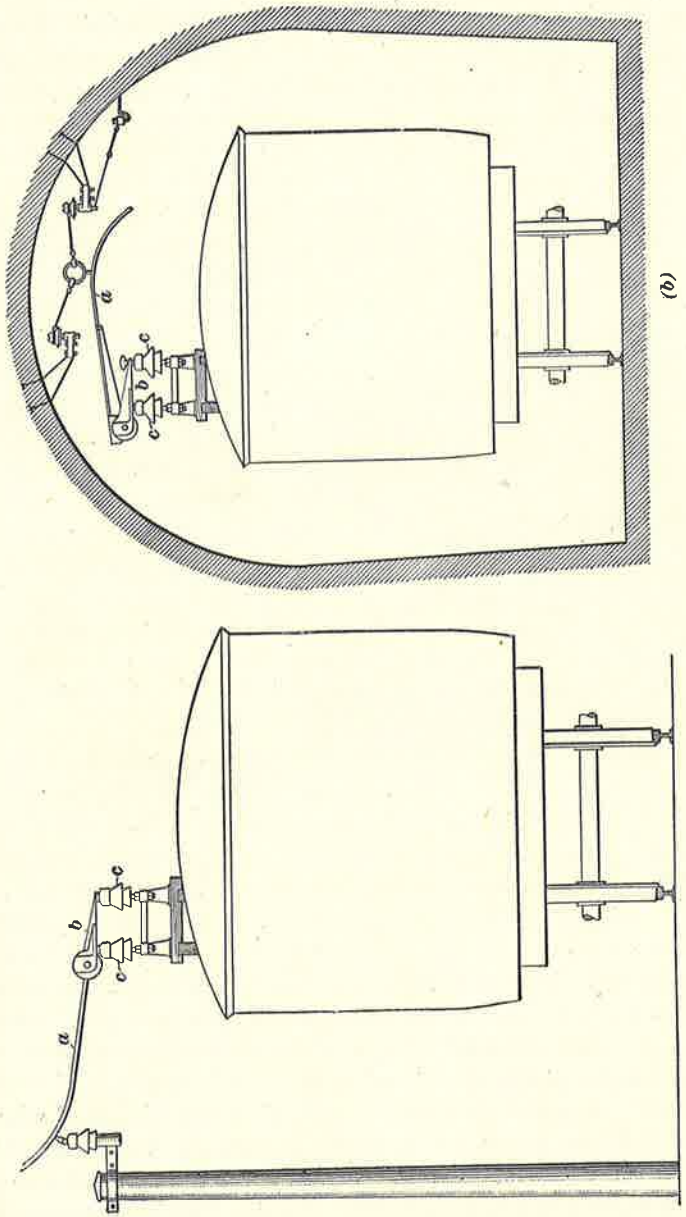


FIG. 43

are bolted to a wooden base fixed to the roof of the locomotive or motor coach. The collector is controlled from the driver's cab by means of a lever, and can be held in the position shown by the catch *d*.

120. Action of Collector.—The two extreme positions of the collector rod are shown in Fig. 43 (*a*) and (*b*), which is lettered similarly to Fig. 42. View (*a*) shows the position of the collector rod when taking current from the upper surface of the conductor, and view (*b*) when collecting from the lower surface in a tunnel. When the collector rod is taking current from the lower surface of the conductor, the weight of the rod opposes the action of the spring, but the collector is so designed that the spring exerts its maximum force in this position. When the contact rod is turned through 180°, and is collecting current from the top of the conductor, the force of the spring is a minimum, and is aided by the weight of the rod. By this means an almost uniform pressure of about $6\frac{1}{2}$ pounds is obtained on the overhead wire for all positions of the collector.

SUSPENSION OF OVERHEAD CONDUCTOR

SINGLE-CATENARY CONSTRUCTION

121. Use of Catenary Suspension.—In order that the overhead conductor may successfully stand the heavy and continual wear to which it is subjected in high-speed railway work, and in order that the insulation may remain sound at the very high pressures used, a special construction which keeps the conductor at practically the same height between main supports is adopted. A trolley wire suspended in the ordinary way sags down between supports in the form of a curve, called a *catenary*. In the **single-catenary construction**, such as is shown in Fig. 44, a messenger, or catenary cable, *a*, usually of stranded steel wire, is supported on insulators on the bracket arms *d*. Short metallic *droppers*, or *hangers*, *c* are used to connect the messenger cable to the hard-drawn copper trolley wire *b*. The hangers are of

such relative lengths and are sufficiently close together that the trolley wire *b* does not sag any appreciable amount. The messenger cable passes through earthed metal loops *f* on the bracket arms, so that in case of breakage the whole section will be earthed.

In some installations the method of supporting the catenary construction shown in Fig. 45 is used. The bracket arm *a* carries the insulator *b*, which has a grooved top in which the catenary cable *c* is placed. The trolley wire *d* is supported below the arm by the hangers *e*.

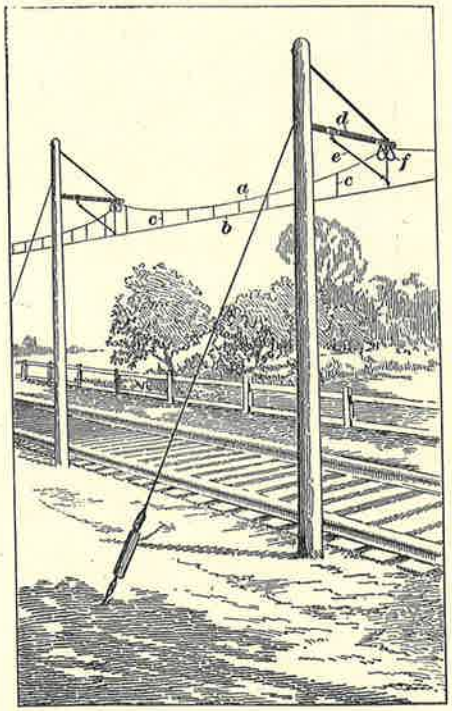


FIG. 44

122. Steady Strain Bracket.—On curves of large radius and at intervals of about 440 feet on straight track, wooden push-off, or pull-off, rods *e*, Fig. 44, are used to keep the catenary construction in an upright position. These wooden rods are fitted at the ends with metal caps, and are attached to porcelain insulators on the bracket arms. A bracket equipped with a push-off or pull-off of this description is known as a **steady-strain bracket.** The details of construction of one type of steady-strain bracket are shown in Fig. 46. The bracket arm *a*, which may consist of a steel tube or **T** iron, is bolted to the pole *b*, and is supported by a tie-rod *c* and brace *d*. A tubular corrugated porcelain insulator *e* on the bracket arm is encircled by a clip which carries the catenary cable *f*. The trolley wire *g* is suspended from the catenary by the dropper *h* and is held in place

by the push-off *i*, which is attached to the brace *d* by the porce-

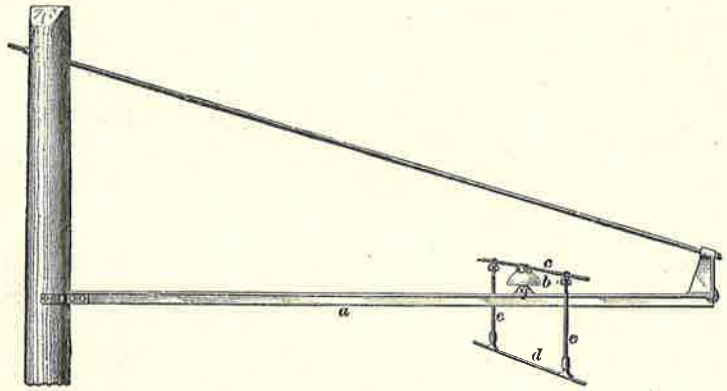


FIG. 45

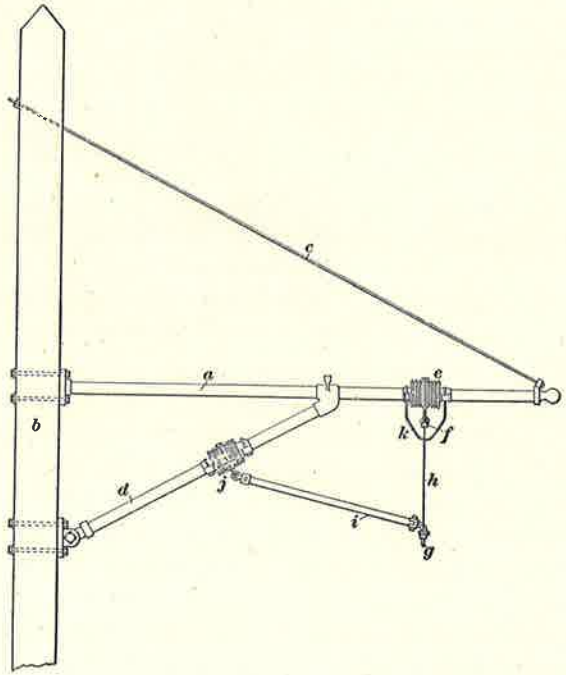


FIG. 46

lain insulator *j*. The earthing loop is shown at *k*. The construction of the tubular porcelain insulator *e* with the earthing

loops is shown in Fig. 47, view (*a*) being a side elevation and view (*b*) an end elevation. The bracket arm *a* is surrounded by

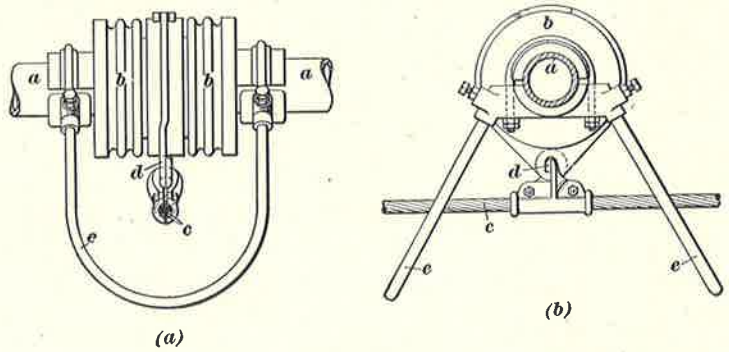


FIG. 47

the porcelain insulator *b*. The catenary *c* is supported by the clip *d* which encircles the insulator *b*. The earthing loops *e* are clamped to the bracket arm *a*, as shown.

123. Hangers.—One type of hanger used to suspend the trolley wire from a single catenary cable is shown in Fig. 48. The catenary cable is encircled by a clamp *a*, and is connected by the steel tube or rod *c* to an ear *b* which grips the trolley wire. The length of the tube or rod is made to suit the position in which the hanger is to be used

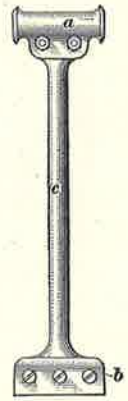


FIG. 48

DOUBLE-CATENARY CONSTRUCTION

124. Arrangement of Double-Catenary Cables. For railways on which traffic is heavy two catenary cables, as shown at *a*, Fig. 49, are used to support the trolley wire *b*. The hangers are triangular in form, the trolley wire being at the lowest point. The catenary construction is usually suspended from steel lattice girder bridges, known as **gantries,** the catenary cables being supported on heavy porcelain insulators mounted on the top of the cross-girder of the gantry. At intervals anchor bridges are erected, at which one section of overhead work is terminated,

and a new one started. The catenary cables on both sides of the anchor bridge are connected to strain insulators and the trolley wires to a section insulator ; the ends of the trolley wire are connected together by a switch mounted on the girders of

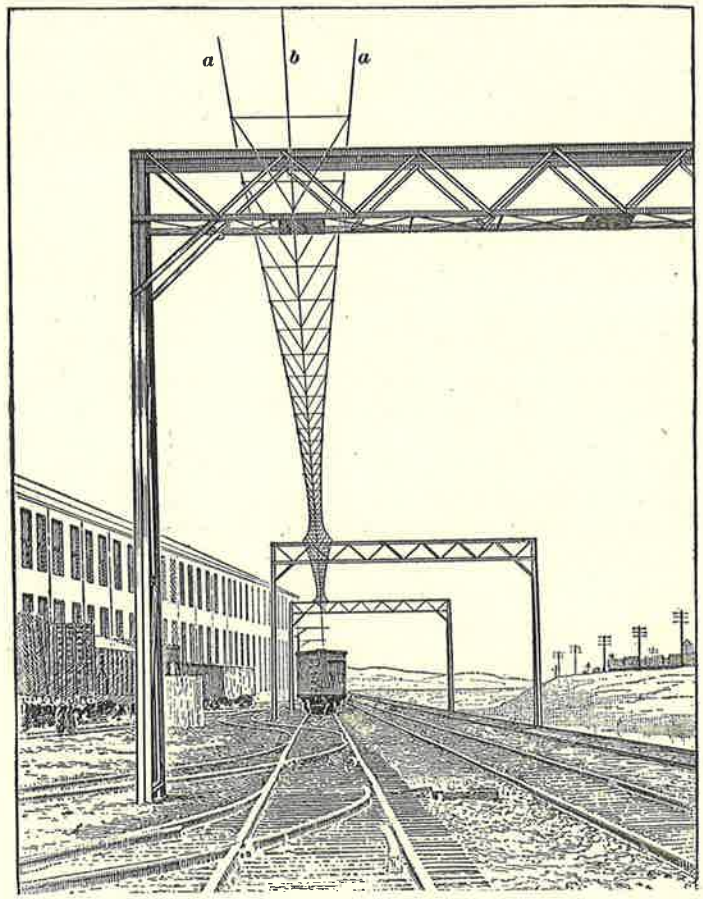


FIG. 49

the bridge, so that the two sections can be disconnected from each other and from the current supply when desired. For single-track railways the cables are sometimes carried by single posts and bracket arms, but this construction is not recommended.

125. Disadvantages of Rigid Suspension.—The form of double-catenary construction just described is too rigid. In one case where the pantograph collector was used its steel bar, owing to the pitching of the locomotive, gave the trolley wire a series of hammer blows, with the result that the conductor was roughened by wear and excessive sparking ensued. Also, the section of the copper wire was soon reduced by wear. Since no provision was made for the expansion of the wire, the slack due to the high temperature was carried in a loop by the collector until a hanger was reached, when a bad kink was formed in the wire; this kink eventually resulted in a fracture. These difficulties have been overcome by the arrangement of the conductors shown in Fig. 50. The catenary cables *a* support the hard-drawn copper

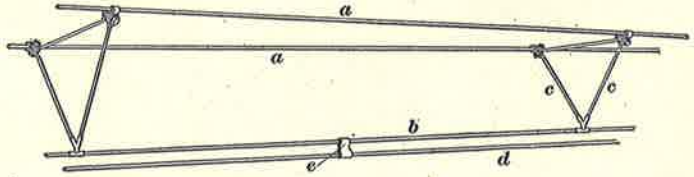


FIG. 50

trolley wire *b* in the usual way by means of hangers *c*. An extra working conductor *d* made of steel is clamped to the trolley wire midway between supports by metal clips *e*. The steel cable thus receives the wear and the copper trolley wire acts as a feeder.

On the London, Brighton, and South Coast Railway each catenary is separately erected and is adjustable by means of two turnbuckles in each span. The droppers, if longer than 3 feet 6 inches, consist of solid rods loosely jointed in the middle by loops. These rods are fixed together at the lower ends by clips, which also hold the trolley wire. Droppers of a shorter length than 3 feet 6 inches have only a loop at the bottom end; these loops are threaded into another loop held by the trolley-wire clip. By these means flexibility is secured.

FITTINGS FOR CATENARY SYSTEMS

126. Push-Offs.—Two types of push-offs, which may be used with either single or double catenary systems, are shown in Fig. 51. That in view (*a*) consists of a stout rod *a* of some

hard wood, such as hickory, fitted with a cap *b* hinged to the casting *c*, which is attached to the pole or bracket arm. The rod is attached to the trolley wire by the cap *d*. The push-off shown in view (*b*) is of the same type and is similarly lettered, but is provided in addition with porcelain and mica insulation, which is shown in detail in view (*c*). The cap at the bracket-arm end of the push-off is provided with a bolt *e*, which passes

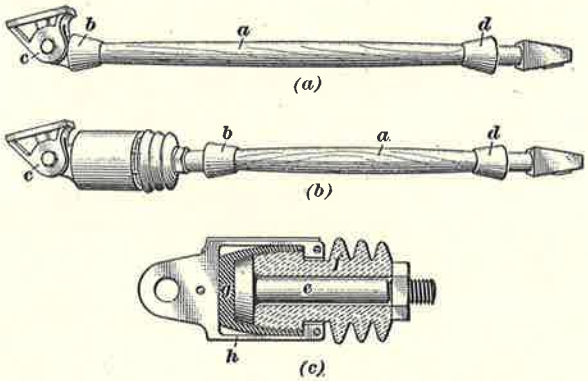


Fig. 51

through the corrugated porcelain insulator *f*. The head of the bolt is protected by the insulating cap *g*, which is made of moulded mica. The head of the bolt, the mica cap, and part of the porcelain insulator are enclosed in a malleable-iron case *h*. Under working conditions, all the insulation is under compression.

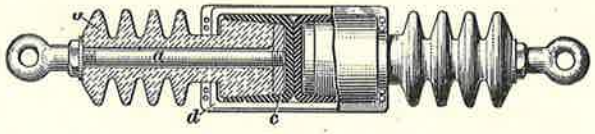


Fig. 52

Even if all the porcelain should break and fall out of the case, the head of the bolt *e* is too large to pass through the opening in case *h*, so that the push-off will not collapse.

127. Pull-Offs.—A well-designed type of pull-off or strain insulator is shown, half in section, in Fig. 52. A bolt *a* passes through the centre of the porcelain insulator *b*, the head of the

bolt being insulated by the moulded mica cap *c*. Both halves of the pull-off are encased in a malleable-iron casing *d*. Insulators of the rod type shown in Fig. 51 are also used as pull-offs.

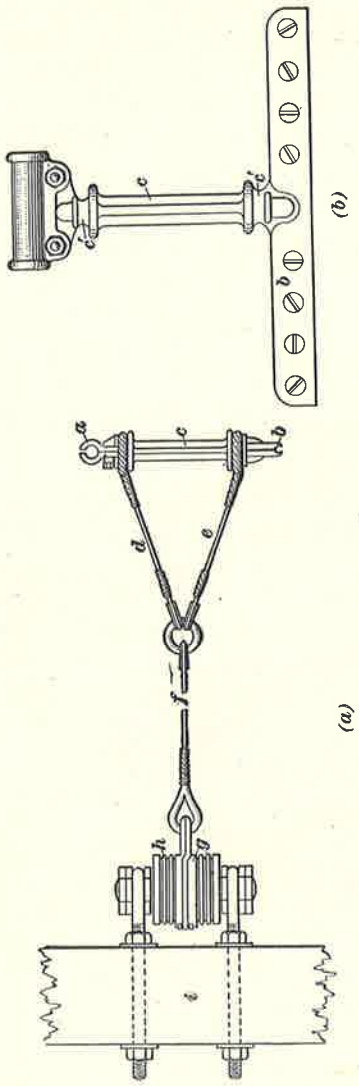


Fig. 53

A good method of using an ordinary tubular corrugated porcelain insulator in connection with a pull-off is shown in Fig. 53 (*a*). The clip *a* is for a single catenary cable, and is connected through the hanger *c* to the trolley wire at *b*. Pull-off wires *d*, *e*, attached to the top and bottom of the hanger, are connected to the single pull-off wire *f*. The other end of wire *f* is fixed to the clip *g* which encircles the corrugated porcelain insulator *h*. This insulator is attached by means of a bolt passing through it to brackets on the pole *i*. The detail of the hanger *c* used for this construction is shown in view (*b*). It will be noticed that the ear *b*, to which the trolley wire is attached, is extra long, and that two grooves *c'*, *c'* are provided for attaching the pull-off wires.

128. Catenary Insulator. One type of insulator used to support the catenary cable is shown in Fig. 54. The outer porcelain petticoat *a* is about 5 inches in diameter, and is

cemented to the inner porcelain petticoat *b*. This is in turn supported on a very deep cup *c* of moulded mica, a packing *d* of spun yarn or other material being placed between the porcelain petticoat *b* and mica cup *c*. The mica cup *c* is carried on a malleable-iron pin *e*, to which it is attached by means of cement.

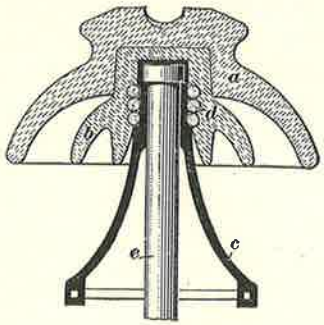


FIG. 54

129. Section Insulators.—Section insulators are used in overhead work of the catenary type, as in other types of railway and tramway work, to divide the line into separate sections. The insulators are generally so arranged that they can be short-circuited by means of a high-tension connecting switch placed at the top of the pole supporting the overhead work, and operated by a long wooden rod. A simple type of section insulator is shown in Fig. 55. It is fastened to the

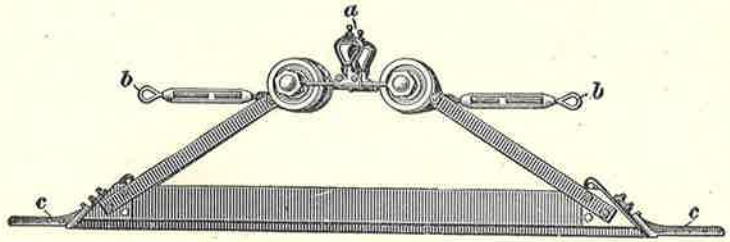


FIG. 55

T-iron support or bracket arm by means of clamps *a*. The catenary cable is attached to the turnbuckles *b* and the trolley wires of the two sections of line to the ears *c*. The running surface between the ears *c* is a strip of hardwood, as in other section insulators. In some cases, section insulators are dispensed with, the end of the trolley wire of one section being suspended parallel to, and about 16 inches distant from, the end of the trolley wire of the other section. The wires are parallel for some distance, but are carefully insulated from each other

130. Deflector Wires.—In order to ensure that the collector bow will pass over the junction of the main and turnout trolley wires, at turnouts and cross-overs, deflector wires are placed in the angle formed by the two trolley wires, as shown in Fig. 56.

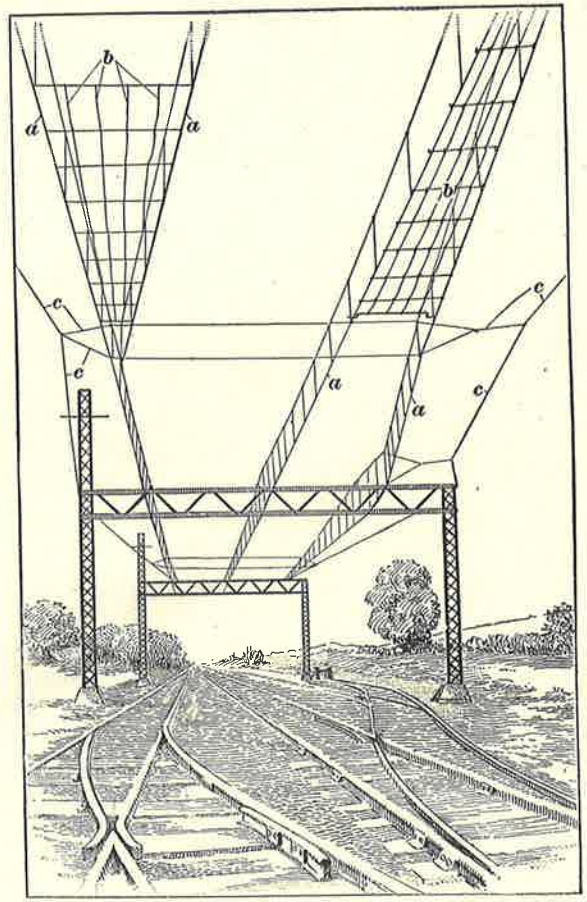


FIG. 56

The trolley wires *a* are connected together by a system of cross wires which carry the deflector wires *b*. The trolley wires are maintained in their proper positions with respect to the track by the pull-off wires *c*. The trolley wire under which the collector

bow is moving is elevated slightly above the other trolley wire by the pressure of the bow, so that, were it not for the deflector wires and the method of mechanically connecting the trolley wires together, which to a certain extent equalize the elevation of the wires, the bow might catch in one of the wires as it approaches a junction.

SIEMENS CATENARY SUSPENSION

131. Arrangement of Cables.—A form of construction installed by the Siemens-Halske Company on a number of railways on the Continent is shown diagrammatically in Fig. 57. The catenary cable *a* is hung on insulators in the usual way from anchor

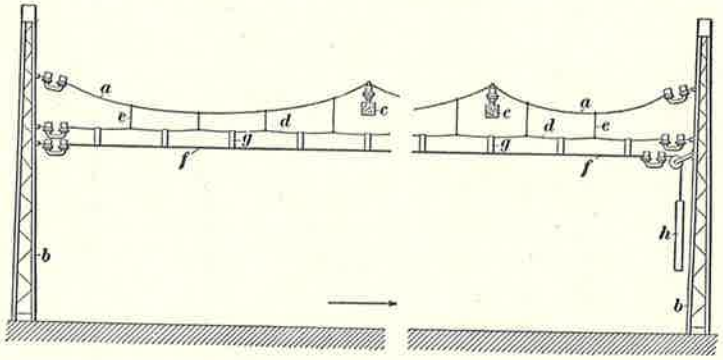


FIG. 57

poles *b* and gantries *c*. From the catenary an auxiliary cable *d* is suspended by means of hangers *e*. The trolley wire *f* is carried by the auxiliary cable *d* by means of special clips *g*. These clips are firmly fixed to the trolley wire, but are free to slide on the auxiliary cable *d*, as shown in Fig. 58, where *a* is the auxiliary wire, *b* the trolley wire, and *c* is the clip. The trolley wire is kept under a constant tension by means of a heavy weight *h*, Fig. 57, which is attached to one end by a chain passing over a

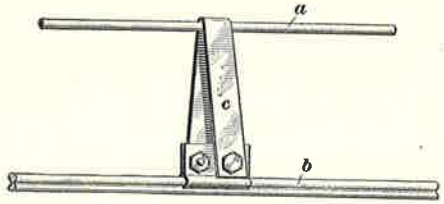


FIG. 58

suitable arrangement of pulleys. The trolley wire is thus free to expand, and all slack is taken up by the weight. The direction

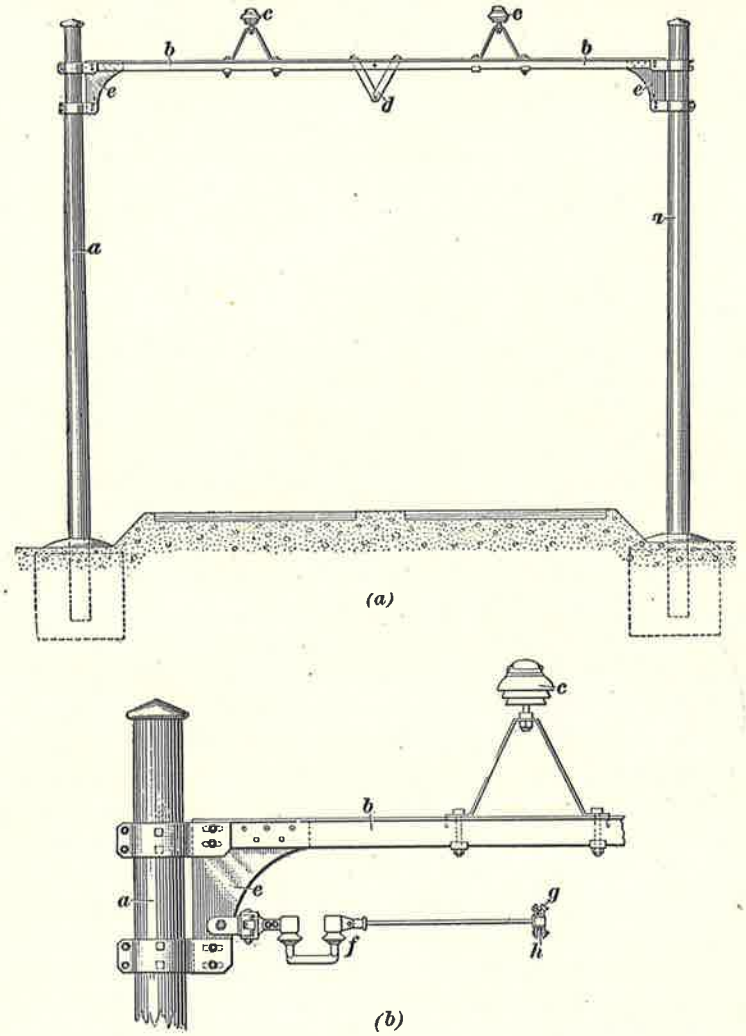


FIG. 59

of traffic, as indicated by the arrow, is such that the collector bow wipes any slack along toward the weight.

132. Construction of Gantry.—The gantries used to support the Siemens catenary construction between anchor poles are arranged as shown in Fig. 59 (*a*). The poles *a* are of wood, and the cross-pieces *b* are of double angle iron, and are bolted to circular clips embracing the poles. The catenary insulators *c* are attached to brackets on the top of the angle irons *b*. The projection *d* and web *e* are used for the attachment of pull-offs or push-offs, as shown at *f*, view (*b*), which gives the detail of the construction. The positions of the auxiliary wire and main trolley wire are shown at *g* and *h*, respectively. Each catenary cable consists of two cables clipped together throughout their length, except for 3 feet on either side of the insulators, where they divide, and pass through grooves in each side of a malleable-iron ring cemented to the head of the insulator. The catenary cable is thus able to move slightly with regard to the insulators, and equalize the tension in the different spans.

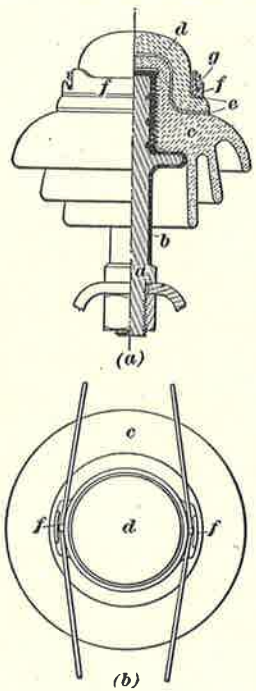


FIG. 60

133. Insulator for Siemens Catenary System.—The construction of the insulator for supporting the catenary wires is shown in Fig. 60, view (*a*) being an elevation, partly in section, and view (*b*) a plan. The insulator is fastened to a mild-steel bolt *a*, round which is moulded a hard-rubber sleeve *b*. Round this sleeve is placed the porcelain insulator proper, which is in two parts *c*, *d*, held together by a layer of cement *e*. The main section *c* of the insulator is provided with three petticoats in order to make the leakage path from the cable to the pin *a* sufficiently long to reduce the leakage to a negligible amount. A malleable-iron ring *f*, cemented round the outside of the porcelain, contains grooves *g* constructed so that the strands of the catenary cable cannot be easily lifted out, but will allow motion along the cable.

FEEDER SYSTEMS ON ALTERNATING-CURRENT RAILWAYS

GENERAL CONSIDERATIONS

134. Sections and Feeders.—Feeder systems for alternating-current railways differ from those for direct-current railways, in that, on account of the much higher trolley voltages employed, the sections into which the working conductors are divided are much greater in length. The actual feeding arrangements adopted depend to a considerable extent on the drop of voltage allowable in the system. On lines which are not very long, extra feeders are not necessary, the working conductor being quite large enough to carry all the current required without excessive voltage drop when fed from one end. Where very long lines with heavy traffic are to be supplied, or where the generating station is at a considerable distance from the line, power is often transmitted at high voltage to transformer substations along the line. These substations contain only the static transformers and switchgear necessary to control the current, and require practically no attention, periodical visits being all that is necessary. When calculating the voltage drop in the overhead conductors, it should be remembered that, as the current is alternating, there is a drop of voltage due to reactance as well as that due to resistance.

135. Steel Rails as Conductors of Alternating Currents.—When an alternating current passes through an iron or steel conductor, the current is not distributed uniformly over the cross-section of the conductor, but is concentrated near the surface of the rail. This is known as the **skin effect,** and is due to the alternating magnetic field set up in the body of the conductor by the passage of the current, this field tending to force the current to the outer surface of the conductor. The equivalent resistance of the conductor is the same as if the current were uniformly distributed over a skin, or shell, on the outside of the conductor. The higher the frequency of the current, the more marked does this effect become.

136. Determination of Equivalent Resistance.—The equivalent resistance of the rail due to this effect varies, for a given frequency, with the magnetic qualities of the iron and the shape of the rail. The equivalent resistance of 1 mile of single rail may, however, be roughly calculated, for frequencies of 40, 25, and 15 cycles per second, by the following formulæ:

Let R_{40} = equivalent resistance of 1 mile of single rail at 40 ~, in ohms;

R_{25} = equivalent resistance of 1 mile of single rail at 25 ~, in ohms;

R_{15} = equivalent resistance of 1 mile of single rail at 15 ~, in ohms;

W_y = weight per yard of rail, in pounds

Then,

$$R_{40} = \frac{24{\cdot}5}{W_y} \qquad (1)$$

$$R_{25} = \frac{20{\cdot}4}{W_y} \qquad (2)$$

$$R_{15} = \frac{15{\cdot}3}{W_y} \qquad (3)$$

EXAMPLE.—Find: (*a*) the equivalent resistance of 2 miles of single track, consisting of two rails weighing 95 pounds per yard, when the frequency of the current flowing is 25 cycles per second; (*b*) the voltage drop in this track when the current flowing along it is 200 amperes.

SOLUTION.—(*a*) From formula 2, the equivalent resistance per mile of single rail is $\frac{20{\cdot}4}{95}$ ohms; that of 2 mi. of single track, consisting of two rails in parallel, is therefore

$$\frac{20{\cdot}4}{95} \times \frac{2}{2} = {\cdot}215 \text{ ohm, nearly.} \quad \text{Ans.}$$

(*b*) The voltage drop, given by multiplying the equivalent resistance by the current, is

$$\cdot 215 \times 200 = 43 \text{ volts.} \quad \text{Ans.}$$

137. Alternating-Current Boosters.—In one respect the feeder system is not entirely settled by the transmission drop allowable. In direct-current practice, it has been laid down by the Board of Trade for tramways, and in some cases for railways, that the difference of potential between any two points of an uninsulated return must not exceed 7 volts. This regulation has been made

in order to protect masses of metal, such as water pipes, in the neighbourhood of the uninsulated return from damage due to electrolysis. At present, there is no Board of Trade regulation dealing with uninsulated return circuits for alternating-current railways; there is only the general obligation on the part of the railway company to pay compensation for any damage that can be proved to be due to any acts of theirs. In view of this, and of any requirement of the Board of Trade that may be laid down, it is general practice to limit the voltage drop in the uninsulated return, not necessarily to 7 volts, but to a reasonably low value. For this purpose, alternate-current boosters, or **sucking transformers,** have been applied in various ways to the feeder systems of alternating-current railways.

138. An alternating-current booster is simply a current transformer with a 1 to 1 ratio. The property of such a transformer is that, over its proper working range, the current in the primary

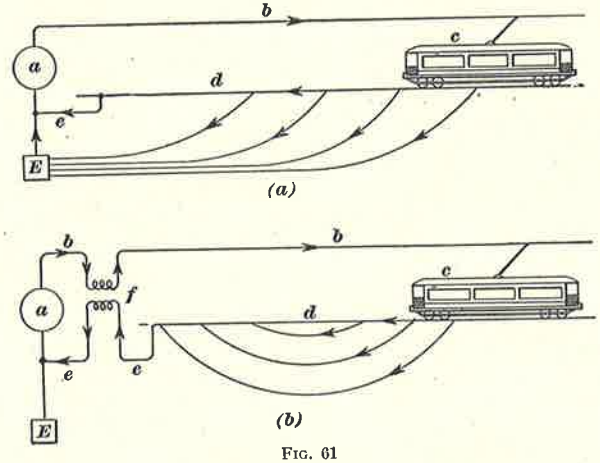


FIG. 61

must be equal to that in the secondary. The method of connection is shown in Fig. 61 (*a*) and (*b*). The alternating-current generators *a* supply current at high voltage over the line *b* to the train *c*. The current returns to the generators by way of the uninsulated track rails *d* and the return feeder *e*. Leakage may occur and a portion of the current may return by way of

the earth plate E, as shown in view (a). In the arrangement shown in view (b) the supply feeder b and the return feeder e are connected, respectively, to the primary and secondary windings of the current transformer f. Then, since the current in the two windings must be practically equal, all the return current must pass through the return feeder e. Thus, although there may be, and probably will be, a little leakage into and out of the

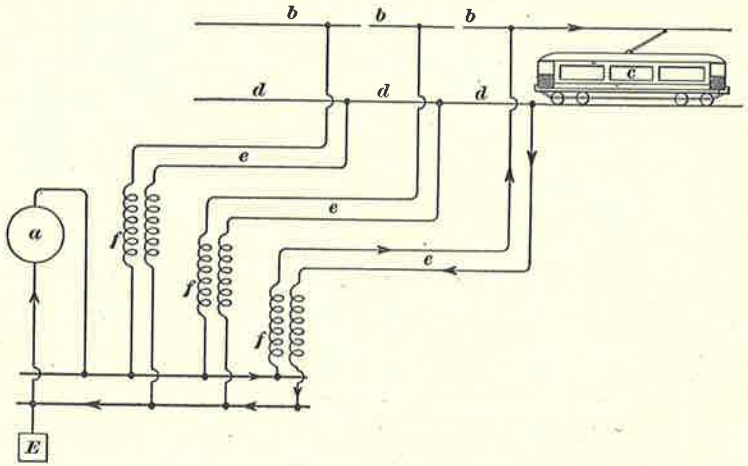


FIG. 62

uninsulated return, as indicated by the arrowheads, the greater part of the return current will pass along the rails, and there will be very little current in the earth. Where separate feeders are used, a sucking transformer should be connected in each, as shown in Fig. 62, which is lettered similarly to Fig. 61. There are several other methods of connecting the transformers to the feeders and return circuit, but the principle of action is the same in all.

ELECTRIC SIGNALLING ON RAILWAYS

SYSTEMS OF SIGNALLING

FORMS OF RAILWAY SIGNALS

EARLY TYPES

1. Necessity for Signals.—The introduction of the modern block-signal systems on large railways has greatly increased the efficiency and safety of train movements. By dividing the tracks into sections, called **blocks**, and installing certain safety devices, one train cannot approach another too closely without passing a warning signal, called a **block signal.**

On some of the early railways, where there was only one train running between two points, no signalling was required. With the development of the railways and the corresponding increase of trains and train movements on the same track, it became necessary to arrange for meeting points of the trains; to install sidings for the passing of the trains; to protect trains moving in the same direction by signals, in case the trains should come nearer to each other than a certain predetermined space; and to protect trains moving in opposite directions by blocking.

2. Ball-and-Mast Signal.—In Great Britain, long before the telegraph was invented, signalling between stations was effected by means of a large ball that was raised or lowered on a high mast. One of these signalling devices was situated at each station and was operated by an attendant, whose duty was to

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